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TENSION, COMPRESSION, AND FATIGUE PROPERTIES OF SEVERAL SAE 52100 AND TOOL STEELS USED FOR BALL BEARINGS

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SUMMARY

Certain mechanical properties of several vacuum-melted tool (hot-work) steels used for high-temperature ball bearings are compared with those of the common high carbon, high chromium, SAE 52100 bearing steel. Various heats of 52100 steel were investigated, namely, three electric-furnace heats and one induction-vacuum-melted heat. The tool steels and one heat of electric-furnace and the vacuum-melted 52100 steel were heat-treated to Rockwell C (Rc) hardnesses ranging from 50 to 65. Particular attention was paid to a hardness of 62 Rc, which in the case of the tool steels was obtained by three different heat-treating practices. The mechanical properties determined were as follows:

(1) At room temperature: Elastic limit, yield strength, and ultimate strength in tension; elastic limit and yield strength in compression; and S-N curves at cycles up to about 100 million.

(2) At 350° F: Yield strength in tension and compression, tensile strength, and S-N curves for the two main heats of 52100 steel.

(3) At 500° F: Yield strength in tension and compression, tensile strength, and S-N curves for the three tool steels, each heat-treated to 62 Rc by three different practices.

The principal results of the investigation are as follows:

(1) Vacuum-melting increases the fatigue strength of 52100 steel at all hardness levels both at room temperature and at a temperature of 350° F.

(2) The effect of hardness on the fatigue strength of 52100 steel, in the range investigated, is small. At 350° F steels with hardnesses between 58 and 65 Rc exhibit practically identical properties.

(3) At room temperature the properties of the tool steels appear to be about equivalent to those of the vacuum-melted 52100 steel. At 500° F the mechanical properties of the tool steels are equal or superior to those of the 52100 steel at 350° F.

(4) The differences between the three tool steels are found to be rather small, with the lower carbon steel (Halmo) exhibiting properties slightly superior to those of the higher carbon steels (M-1 and MV-1).

(5) There exists no simple relation between fatigue strength and any static property.

(6) The stress-strain relations of very hard steels are rather different for tension and compression. This nonsymmetry (which has a similarity to the Bauschinger effect) gradually disappears at elevated temperatures.

INTRODUCTION

The most usual steel for ball bearings is SAE 52100 steel heat-treated to a Rockwell C (Rc) hardness of approximately 60. Its performance in ball bearings depends largely upon the steel-making practice. Until 1946 a gradual improvement in bearing life was observed and was presumably caused by the general progress in electric-furnace steel making and particularly by progress in improving the cleanliness of the steel (ref. 1).

The dependence of ball-bearing performance upon steel-making practices is probably associated with the fact that the steel properties are generally inferior in the direction perpendicular to the "fiber." This applies particularly to the fatigue strength (refs. 2 to 4). Fatigue tests on ball bearings also confirmed that their life is much longer if they are run with the maximum stresses occurring in directions most favorable in respect to the fiber, rather than in the most unfavorable direction (ref. 5). Furthermore, it is observed that fatigue cracks usually develop at inclusions near the surface (ref. 6).

The elimination of inclusions by vacuum-melting resulted in an improvement of bearing performance (ref. 1). This is associated with the fact that the spread in the life of bearings under identical conditions is usually (but not consistently) less for vacuum-melted than for electric-furnace-melted steel; the maximum life of bearings which perform best appears to be approximately equal, but the minimum life is found to be greatly improved by vacuum-melting (ref. 7).

Conventional fatigue tests on 52100 steel (ref. 8) and on 4340 steel (ref. 9) also revealed a considerable increase in endurance limit by vacuum-melting (particularly for 4340 steel in the transverse direction).

The need for longer bearing life at elevated temperatures, which exceeds the useful life range of heat-treated 52100 steel, leads to the use of vacuum-melted, high-alloy tool steels (refs. 1, 7, 10, and 11). These steels develop and retain high hardness up to about 1,000° F since their initial hardness is obtained by tempering at a temperature exceeding 1,000° F because of the process of "secondary hardening." The tests on some such steels have confirmed their expected superiority over 52100 steel at elevated temperatures up to 450° F, while 52100 steel, heat-treated to hardnesses of over 60 Rc, is already unstable below this temperature and has an assumed upper limit of 350° F for its usefulness.

While it appears established that bearing life is a fatigue phenomenon, fatigue testing is rather tedious, even in its simplest form. On the other hand, tension and compression tests are performed rather readily. Therefore, if it were possible to correlate fatigue life with any static property, evaluation of bearing materials would be facilitated. Some claims of the existence of such a correlation have been made, particularly one that the elastic limit of steels might be used for this purpose (ref. 12).

A general project has therefore been set up by the National Advisory Committee for Aeronautics to evaluate (a) the effects of vacuum-melting and (b) the performance of several vacuum-melted tool steels suggested for bearing applications. The research program described in the present paper was part of this project, was conducted at Syracuse University under the sponsorship and with the financial assistance of the NACA, and was primarily aimed at answering the following questions:

(1) What is the room-temperature relation between hardness and elastic limits in tension and compression for tool steels heat-treated to high hardness levels? In particular, is there a limiting hardness which, if exceeded, results in a breakdown of tensile and compressive properties?

(2) For the same steels, is there a correlation between the elastic limits in tension and compression and the room-temperature endurance limit in rotating-beam fatigue results?

(3) Are the above relationships maintained at elevated test temperatures?

The authors are indebted to Mr. W. F. Brown, Jr., of the NASA Lewis Research Center for suggestions and criticism in evaluating the problem and the results. They also wish to acknowledge the assistance of the following Syracuse University Research Institute personnel: Mr. R. Bale and Mr. W. Lipa in the development of the equipment and the execution of the tests and Mr. A. Viggiano in the compilation of the test data.

MATERIALS

An electric-furnace heat (heat 1) and an induction-furnace vacuum-melted heat of 52100 steel, as well as vacuum-melted heats of three tool steels (Halmo, M-1 (AISI TMO), and MV-1 (AISI M-50)) were obtained from the Crucible Steel Co. of America, Syracuse, N.Y. Two additional electric-furnace heats of 52100 steel (heats 2 and 3) were made available in small quantities by the Marlin-Rockwell Corp., Jamestown, N.Y. The steels used for the tests were in the form of 1/2-inch-diameter rods except for heats 2 and 3 of 52100 steel which were in the form of 9/16-inch-diameter rods.

The chemical composition of the steels is given in table I and the hardenability of the two principal 52100 steel heats is compared in figure 1 with that of a "typical" heat. The hardenability was determined on W
5-inch-long 1/2-inch-diameter specimens by means of a modified quenching 1
fixture. An inclusion count was made on the steels by the Allegheny 3
Ludlum Steel Corp., Pittsburgh, Pa., with the results assembled in 1
table II.

The various heat treatments of the steels, leading to Rockwell C (Rc) hardnesses between 50 and 65, are given in table III. The 52100 steel heats were quenched and tempered in the conventional manner. Each of the three tool steels was subjected to an experimental heat treatment yielding hardnesses between 50 and 65 Rc, and, additionally, to two different commercial heat treatments leading to a hardness of 62 Rc which were recommended and performed by the Marlin-Rockwell Corp. and the Crucible Steel Co. of America. All the other specimens were heat-treated by the Marlin-Rockwell Corp.

The fatigue specimens heat-treated by the commercial method were badly warped and decarburized. The resulting test data scattered widely (over two orders of magnitude in the number of cycles for equal stress) and fatigue failures still occurred at stresses greatly below the endurance limit of the other two heat treatments. These results, therefore, have been discarded and are not reported.

X-ray diffraction studies were made for an estimate of (1) residual surface stresses, (2) microstresses, and (3) presence of carbide and retained austenite and are discussed in the appendix.

TEST PROCEDURES

Tension Tests

The main problem in tension-testing very hard steels is obtaining concentricity of loading. Tensile strength values well above 300,000 psi can be obtained with special fixtures such as those developed and generally used for notch tests (see ref. 13). Common grips may result in brittle breaks at high hardnesses and limit the tensile strength to values as low as 250,000 psi (see ref. 12). In the present investigation special grips were used; even the high-carbon 52100 steels yielded tensile strengths up to nearly 350,000 psi, and the tool steels had strengths well over 350,000 psi. Strain gages at three locations along the circumference of a few specimens revealed, according to figure 2, nearly perfect concentricity in tests with such a notch tension fixture.

The tension specimens had a gage length of 0.400 inch and a diameter of 0.187 inch and were connected by a 2.5-inch radius with the threaded ends. The preparation of the specimens consisted of rough machining to about 0.220-inch diameter before heat-treating, and grinding and polishing after heat-treating.

Most of the room-temperature tests were calibrated with strain gages up to the 0.2-percent yield strength and after that with extensometers attached to the grips with the aid of extension rods. In the high-temperature tests only the extensometer was used with the specimen, the grips, and the greater portion of the extension rods located within the furnace. To allow for plastic flow outside the gage length an "effective" gage length of 0.5 inch was used to determine the yield strength. The values of yield strength at room temperature, determined by either strain gages or extensometers with extension rods, were found to be in good agreement. A perfect strain-gage method has not been developed for use at elevated temperatures, and all tests were performed by using the mechanical extensometer.

Compression Tests

Compression tests on hard materials also need special provisions in order that concentric loading can be obtained. The eccentricity encountered in testing a cylindrical specimen between flat parallel plates in the usual manner may be, according to figure 3(a), rather high and may result in widely varying strain-gage readings. Good concentricity in the present tests was obtained by rigid guiding of the compression fixture by means of a precision die set and by polishing the accurately machined square specimen ends to a very slightly rounded contour. That good concentricity was produced is illustrated by figures 3(b) and 3(c).

To allow uniform heating of the specimen the pressure plates were extended sufficiently deep into a split electric furnace to produce a temperature uniform over the specimen length within ±2° F.

The compression specimens had a diameter of 0.333 inch and a length of 1.000 inch. The preparation of the specimens consisted of rough machining to about 0.370 inch before heat-treating and grinding and polishing after heat-treating.

Elastic limit and yield strength were determined in much the same manner as in tensile tests.

Determination of Elastic Limit and Yield Strength at Room Temperature

The elastic limit and the yield strength of most specimens tested at room temperature were determined by means of SR-4 strain gages. Actually, bonded-wire strain gages are not generally used up to the high strains encountered here, and the peculiar and unexplained phenomena previously reported in reference 12 and confirmed and reported below may have their origin in some characteristics of the strain-gage attachment.

In these tests the load was increased in small increments and released to zero after each increase in order to determine the permanent set. The high sensitivity of the strain-gage method reveals the first permanent strains to be the reverse of those expected. Figure 4 illustrates for two examples the strains under load and the permanent strain after load release. If the permanent strains are represented on a large scale, reverse strains apparently occur first which, for certain treatments and testing in compression, may become as large as 0.03 percent before permanent strains in the right direction are observed. The gage readings were terminated at slightly over 0.2-percent permanent strain, and the tests finished with the mechanical strain gage. The load readings also yield the modulus of elasticity (tangent modulus at zero load). Typical sets of permanent strain data for heat 3 of 52100 steel are illustrated in figure 5(a) for tension and in figure 5(b) for compression.

The elastic limit is defined here as the highest stress for zero permanent strain. This is an arbitrary definition, but no other value is obtainable to better accuracy, and the physical meaning of any other definition remains obscure. For purposes of comparison, this definition serves as well as any other. The yield strength, taken as the stress for 0.2-percent permanent strain, is also subject to some doubt. However, it appears that any error introduced by this test method is well within the limits of accuracy (see fig. 4).

Figure 6 assembles the moduli of elasticity in tension and compression for all steels investigated. At the highest hardnesses comparatively low values were observed in a number of instances. This may have some fundamental significance and relation to the low values of elastic limit and yield strength.

Fatigue Tests

The rotating bending-fatigue-test method was selected for this investigation on recommendation of the advisory NACA Committee for Bearing Materials. Tests at room temperature were performed with R. R. Moore high-speed rotating bending-fatigue machines, using hour-glass-shaped specimens of standard design having a diameter of 0.187 inch and a contour radius of $2\frac{7}{8}$ inches.

For elevated-temperature tests a modified high-speed fatigue-testing machine was developed from an R. R. Moore type fatigue machine. This machine was constructed with a longer base which increased the distance between the spindles by $3\frac{1}{2}$ inches and permitted the installation of an electric resistance furnace and two cooling jackets which fastened to the faces of the spindle housings. Several of these machines were built from elements of R. R. Moore machines. The high-temperature fatigue specimens correspondingly differed from normal specimens by having a $1\frac{3}{4}$-inch cylindrical length at each end between the hour-glass test section and the tapered ends. Temperature control was effected by inserting a thermocouple into a bore through one end of the specimen to a position 7/8 inch from the minimum section or center of the specimen. The difference between the temperatures at the two sections, that is, between the control and the specimen temperature, was determined by calibration with a specimen at rest.

The preparation of the specimens consisted of rough machining to about 0.230-inch minimum diameter before heat-treating and grinding, followed by longitudinal polishing to a high finish after heat-treating.

Thirty specimens each were available for each test series in the early tests. After some preliminary testing, it was decided to test at least five specimens at each of the lower strength levels, whenever possible, to allow a reasonably accurate determination of the fatigue strength at 10^7 and 10^8 cycles. In contrast with the behavior of softer steels, the S-N curves of the steels tested exhibited no sharp decrease in slope up to 5×10^7 cycles. The tests on unbroken specimens were discontinued between 5×10^7 and 10^8 cycles. The scatter of the fatigue strength at 10^7 and 10^8 cycles is approximately ±10,000 psi.

In later tests only a very limited number of fatigue specimens were available, with a corresponding further decrease in the accuracy of the data reported.

RESULTS OF STATIC TESTS

Historical Background

Results of static tests on very hard steels having a carbon content of over 0.5 percent and heat-treated to hardnesses of 55 Rc or higher are infrequently reported and these data are only in part consistent. It appears that bend tests are the easiest and most reliable method of testing such steels (refs. 14 and 15). Values of bend strength, or transverse modulus, which increase with increasing hardness to well over 600,000 psi at hardness values in excess of 60 Rc and then again decrease at still higher hardnesses have been obtained by either three-point or four-point loading.

Tensile tests on such hard steels frequently yield low values because of eccentric loading. With normal loading fixtures, brittle fractures, associated with maximum values of tensile strength in the vicinity of only 250,000 psi at a hardness of about 50 Rc, are frequently obtained (ref. 12). In contrast, the use of special centering fixtures consistently yields, for very hard steels, tensile strengths between 300,000 psi and 350,000 psi or even more (refs. 13 and 16).

The yield strength of steels in tension is usually found to pass through a rather flat maximum at a hardness near the maximum value for the particular steel. However, a survey of existing data indicates that the yield strengths of steels of high hardnesses depend considerably upon the heat-treating practice (ref. 13).

The yield strength in compression of hard steels has been observed to be greater than that in tension, with the difference increasing with hardness (ref. 16). It appears that no maximum exists in the compressive yield strength.

In the early days of testing metals and alloys great significance was ascribed to the so-called elastic limit. The necessary tedious procedure of loading and unloading, the lack of a clear definition, and the variability of this limit with small differences in treatment had generally caused abandonment of the elastic limit as a reliable criterion of strength. However, recently attempts have been made to revive the importance of the elastic limit as determined by strain-gage measurements which indicate extremely small reverse permanent strains before the onset of plasticity (ref. 12). By this method, the tensile elastic limit of heat-treated carbon steels was found to exhibit a pronounced maximum at a certain intermediate hardness and to become extremely low at very high hardnesses. This phenomenon is in agreement with the well-known fact that the stress-strain curve changes from a shape with a well-defined yield point to a rather smoothly rounded off curve as the hardness increases to very high values. However, the peculiar reverse permanent strains observed in the strain-gage tests cannot be explained. Since the stress values in such tests are generally high and above those in which strain gages are considered reliable, some doubt is raised as to the nature of this effect. Nevertheless, the method appears to have merit for determining values of elastic limit which, at least, are well defined.

Regarding the further claim that elastic limit and endurance limit of hard steels are closely related, the following facts may be stated. The evidence presented in support of this claim is limited to a few steels, mostly with 0.4 percent carbon, and only part of the information available has been used. For steels with higher carbon content elastic limits between 30,000 and 60,000 psi have been reported while the fatigue strength of such steels heat-treated to high hardnesses has already been determined by early investigators to be between 70,000 and 100,000 psi (ref. 17).

Tests at Room Temperature on 52100 Steel

The results of the room-temperature tension and compression tests on the various heats of 52100 steel are assembled in figure 7. Typical stress-strain curves for these steels, obtained as averages of two to four tests for the regular electric-furnace and vacuum-melted heats, are given in figure 8.

The four different heats of 52100 steel are found to possess practically identical tension and compression properties at all hardness levels up to 58 Rc. The heats differ in properties only at the highest hardnesses and, according to figure 7, only in their tensile strengths and, presumably, in their ductilities which determine their tensile strengths. However, because of the low values of ductility which for these hardnesses did not exceed 1/2 of 1 percent, these could not be measured accurately.

The difference in the tensile strengths at the high hardnesses does not conform to expectations, since the strength of the vacuum-melted heat is found to be below that of the regular electric-furnace heat. Also, no explanation can be given for the wide spread in the strength of the three electric-furnace heats.

The yield strength and elastic limit of these steels for tension are rather different from those for compression. In tension, these values first increase with increasing hardness, but then pass through a maximum at 58 Rc. At higher hardnesses, the yield strength decreases slightly and the elastic limit, considerably. This fact has been long recognized as being characteristic for oil-hardened steels (ref. 13), but has not yet been explained. In contrast, the yield strength in compression increases with increasing hardness over the entire range of hardnesses. However, the elastic limit in compression again passes through a pronounced maximum. Furthermore, the yield strength and, particularly, the elastic limit in compression were observed to be higher than those in tension. This difference increases considerably as the hardness becomes higher. Again, no explanation can be given for these phenomena.

The stress-strain curves in tension and compression (fig. 8) also illustrate the above-discussed relation. In addition, these curves illustrate the well-known change in contour with increasing tempering temperature from a rather smooth shape at 65 and 62 Rc to a curve with a distinct break at the lower hardnesses.

Tests at Room Temperature on Tool Steels

The results of the tests on tool steels are assembled in figure 9. Stress-strain curves are presented in figure 10 for the Halmo steel.

Again the relations between hardness, tensile strength, and yield strength differ only slightly for the steels at hardnesses up to 58 Rc. At 62 Rc the tensile yield strength of the three steels was also found to be substantially the same, while the compressive yield strength of three specimens tested was consistently considerably lower for MV-1 steel. At the highest hardness, 65 Rc, the Halmo steel exhibited a higher strength than the other two steels, while the yield strength in both tension and compression differed only slightly.

The elastic limits of Halmo steel were found to be higher than those of the other tool steels at hardnesses up to 58 Rc. At 65 Rc the three steels had approximately the same yield strength. At 62 Rc the MV-1 steel exhibited an extremely low compressive elastic limit in agreement with its low yield strength. Otherwise, the values of Halmo were slightly below those of the other two steels.

The differences between the Halmo steel and the two other steels may be associated in part with their different carbon contents. However, no explanation can be given for the peculiar relations governing the elastic limits and, to a minor extent, the yield strengths. It is expected that the complex structural changes occurring on tempering have a considerable effect on the shape of the stress-strain curve at the onset of plasticity, but no definite information is available in this respect.

The properties of the tool steels differ from those of the 52100 steels in many respects, but tensile strength and yield strength differ only to a minor extent at hardnesses up to 58 Rc. Again no explanation can be given for the variations at the higher hardnesses or in the elastic limits or in the maximum values of tensile strength.

Tests at Elevated Temperatures

A number of tests were also performed at 350° F with the electric-furnace heat 1 of 52100 steel, which was heat-treated to various hardness, and at 500° F with the three tool steels, which were heat-treated to 62 Rc.

The tension and compression properties of the 52100 steel at 350° F are shown in figure 11. They show a considerably different dependence upon hardness at this temperature from that at room temperature (see fig. 12).

The effect of test temperature at hardnesses up to 58 Rc conforms to the previously established behavior pattern of low-alloy steels (ref. 13). The tensile strength remains nearly constant in this temperature range, while the yield strength in either tension or compression at 350° F is 10 to 15 percent lower than at room temperature.

At hardnesses of 62 Rc and 65 Rc the strength properties of the 52100 steel were found to be practically identical with those at a hardness of 58 Rc. This is explained by the fact that these tempers are not stable at 350° F but are subject to further tempering. This also means that the peculiar dependence of yield strength (and elastic limit) upon hardnesses at room temperature vanishes at 350° F. As a consequence, the tensile yield strength is found to increase slightly for a hardness of 62 Rc and considerably for 65 Rc when the test temperature is raised to 350° F. The compressive yield strength is affected very differently; it is reduced by nearly 30 percent for 62 Rc and nearly 40 percent for 65 Rc by increasing the test temperature. These phenomena are also illustrated by the change in the general shape of the stress-strain curves (see fig. 8). The tensile strength of the hardest temper investigated, 65 Rc, was also slightly increased, as was to be expected.

The few tests on the tool steels heat-treated to about 62 Rc revealed, according to table IV, that raising the test temperature to 500° F reduces the tensile strength by about 10 percent, the tensile yield strength hardly at all, and the compressive yield strength (with the exception of the initially low value for the MV-1 steel) by about 15 percent.

The main fundamental results of these tests may be considered to be that the stress-strain relations of very hard steels are rather different for tension and for compression, and that this nonsymmetry (which has some similarity to the Bauschinger effect) gradually disappears at elevated temperatures.

RESULTS OF FATIGUE TESTS

Tests at Room Temperature on 52100 Steel

The results of fatigue tests on the various heats of 52100 steel are assembled in figure 13. They agree with earlier test data on this steel composition (refs. 2, 7, 8, 18, 19, and 20) in that the endurance limit at 10^8 cycles varies only slightly with hardness for hardnesses of 50 Rc or higher. At a lower number of cycles the fatigue strength is found to vary directly with the hardness. The fact that the fatigue properties are maintained at high values up to the highest hardnesses obtainable with the particular steel composition has been repeatedly confirmed (see refs. 3, 4, and 19). Results of rather recent tests which show a severe drop in fatigue life at high hardnesses (ref. 21) are rather difficult to explain in the light of such evidence.

The numerical values for the endurance limit of different hardnesses of 52100 steel determined in the present investigation, however, are found to differ greatly from those of other investigators. No explanation can be given for variance in the values reported for electric-furnace heats from about 75,000 psi (ref. 2) to about 125,000 (ref. 8) or even higher (ref. 19).

On the other hand, it appears to be established that the endurance limit of 52100 steel depends considerably on steel-working practices. As noted in figure 14, vacuum-melting improves the endurance limit by about 10,000 to 20,000 psi for the steels investigated here. This effect appears to decrease as the hardness increases. The favorable effect of vacuum-melting has been previously reported (ref. 8) and appears now established for this and other steel compositions.

Another effect of steelmaking has also been previously reported, namely, higher values of endurance limit for open-hearth heats than for electric-furnace heats (ref. 2). This difference has not been explained, but it may be related to the fact that the three electric-furnace heats investigated here possessed considerably different fatigue properties. It is apparent from figures 13(c) and 13(d) that the two special heats exhibited at 62 Rc endurance limits 10,000 and 20,000 psi, respectively, lower than that of the heat which had been primarily investigated.

It has been claimed that the frequently very large scattering of fatigue test data for hard steels is explained by the size of the surface or subsurface inclusion at which the fatigue crack usually originates (refs. 22 and 23). A macro- and micro-examination of a number of specimens which failed at extreme numbers of cycles, however, failed to reveal any significant difference in their inclusion pattern.

Tests at Room Temperature on Tool Steels

The three tool steels commercially heat-treated by the Marlin-Rockwell Corp. to approximately 62 Rc were tested at room temperature with the results given in figure 15. The fatigue strength of the Halmo steel was found to be nearly 10,500 psi higher than that of the M-1 steel and about 25,000 psi higher than those of the MV-1 steel.

The fatigue strength and endurance limits of these steels do not differ materially at room temperature from those of the vacuum-melted 52100 steel (figs. 13 and 14). For the investigated hardness level of 62 Rc, all four steels are found to possess an endurance limit of about 120,000 ± 15,000 psi. This, of course, applies only to steels produced by the same steel-making practice and of identical cleanliness (see ref. 7).

Tests at Elevated Temperatures

The results of tests on the electric-furnace heat of 52100 steel reveal, according to figures 16 and 17, a decrease in endurance limit of about 15,000 to 25,000 psi when the test temperature is increased from room temperature to 350° F. At hardnesses 58 Rc and higher the effect of elevated temperature is more pronounced; this possibly indicates the unstable structure of these hardnesses at 350° F. The three highest hardnesses of the electric-furnace heat investigated yielded practically identical fatigue properties. Only a few test specimens were available for the vacuum-melted 52100 steel. The favorable effect of vacuum-melting appears, according to figure 17, to be considerably smaller at 350° F than it was at room temperature.

In regard to the results of tests on the tool steels at 500° F, figure 18 indicates a large scattering of the test data which renders the fatigue strength values rather inaccurate. The most consistent results were obtained with the Halmo steel, in regard to both the scattering of results for each heat treatment and the agreement between the two heat treatments shown in figure 18. The Halmo steel and the M-1 steel exhibited nearly identical average fatigue strength values of about 100,000 psi for 5×10^7 cycles. The MV-1 steel yielded an average value of only 90,000 psi when both heat treatments were considered, but the values for the two treatments varied by about 20,000 psi, with the commercial heat treatment resulting in a value as high as or higher than those for the other two steels. These values are noticeably higher than that of the vacuum-melted 52100 steel tested at 350° F. The tool steels, therefore, can be used to temperatures at least 150° F higher than can the 52100 steels.

The third heat treatment investigated yielded extreme scattering of the test values and, therefore, the results are not reported. The average values were possibly 30,000 psi lower than those mentioned above. This is explained by the severe warping of the test specimens and the resulting difficulty of completely removing the rather deep decarburized surface layer.

COMPARISON OF FATIGUE AND STATIC PROPERTIES

The foregoing discussion clearly indicates that the factors which control fatigue properties are fundamentally different from those which control static properties. The following differences are to be especially noted:

(1) Static properties are predominantly dependent upon the hardness level, which has almost no effect on endurance limit if the hardness is very high.

(2) Steel-making practices affect the fatigue properties considerably, but they affect the (longitudinal) tensile and compressive characteristics only insignificantly.

(3) Differences in heat-treating practices may influence fatigue properties to a much greater extent than they affect static properties.

Both the static and the fatigue characteristics of heat-treated steels are dependent upon a rather large number of factors, the basic nature of which is still little recognized. The rather large effects of these factors, in certain instances, are rather surprising in view of the numerous attempts to establish simplified universal relations between different properties.

CONCLUSIONS

The phenomena revealed by the present investigation of the tension, compression, and fatigue properties of several 52100 and tool steels are complex and cannot be explained. Consequently, their fundamental and practical significance is obscure. For practical purposes, the following conclusions now appear sufficiently substantiated:

(1) No static stress limit which has any bearing on fatigue strength and endurance limit exists.

(2) Tool steels with a hardness of 62 Rc and a softening temperature on tempering in excess of 1,000° F possess, when tested at 500° F, static and dynamic properties superior to those of 52100 steel heat-treated to 62 Rc at a working temperature of 350° F.

Syracuse University,
Syracuse, N.Y., October 28, 1958.

APPENDIX

X-RAY DIFFRACTION STUDIES OF SEVERAL

52100 AND TOOL STEELS

Five alloy steels (cf. table V) were investigated by X-ray diffraction methods on a comparative basis. The following quantities were determined for all steels and hardness levels:

(1) The interplanar spacing of the (211) planes parallel to the specimen surface

(2) The width of the (211) diffraction line at half-peak intensity

(3) The presence or absence of retained austenite and carbides

The X-ray studies were made on a General Electric XRD-5 diffraction unit with a proportional counter using vanadium oxide filtered chromium $K\alpha$ radiation. The results are presented in table V and in figures 19 and 20.

In table V the interplanar spacings $d_{(211)}$ of the (211) planes, the peak intensities, the half widths, and the presence or absence of carbides and retained austenite are listed as a function of hardness level for the alloy steels investigated. Figure 19 shows the $d_{(211)}$ values as a function of hardness levels for all steels and figure 20 is a plot of the widths or half intensity of the (211) diffraction lines as a function of hardness level.

From figure 20 it can be seen that the $d_{(211)}$ value increases for all steels with increasing hardness level. Since this $d_{(211)}$ value was determined from planes oriented parallel to the specimen surface, an increase in $d_{(211)}$ is equivalent to an increase in compressive circumferential surface stress. Based on this concept a change of the $d_{(211)}$ value by 0.0010 angstrom represents a change in stress of approximately -30,000 psi. However, this figure should be used for order-of-magnitude-type comparisons only.

The widths of the (211) diffraction line are plotted against hardness in figure 20. According to this figure the line width also increases almost uniformly with increasing hardness level. Among the factors responsible for increase in diffraction line widths are microstrains, particle size, and plastic deformation; the most significant contribution in the present case is microstrain. On this basis an increase of the line width at half intensity of 1° corresponds to an increase of the microstrain level of approximately 2×10^{-3}. This figure should also serve for semiquantitative evaluation only.

The amounts of carbide and retained austenite present were found to depend on the alloy more than on the hardness level. In some cases (Halmo and M-1) the tendency of a slight increase in amounts of carbides and retained austenite present with increasing hardness levels were observed (cf. table V).

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TABLE I

CHEMICAL COMPOSITIONS OF INVESTIGATED STEELS

Alloy	C	Mn	P	S	Si	Cr	V	W	Mo	Cu	Ni
52100, electric furnace, heat 1	1.03	0.32	0.01	0.02	0.29	1.49	----	----	0.01	0.05	0.08
52100, electric furnace, heat 2	1.02	0.41	0.01	0.01	0.30	1.43	----	----	0.02	0.11	0.08
52100, electric furnace, heat 3	1.06	0.34	0.01	0.01	0.30	1.43	----	----	0.02	0.12	0.13
52100, induction vacuum melt	1.05	0.37	0.002	0.007	0.26	1.51	----	----	Trace	0	0.02
Halmo, induction vacuum melt	0.59	0.31	0.005	0.007	1.10	4.79	0.51	----	5.22	----	----
M-1 (AISI TMO), induction vacuum melt	0.80	0.25	0.004	0.007	0.32	3.76	1.15	1.53	8.54	0.01	0.07
MV-1 (AISI M-50), induction vacuum melt	0.81	0.26	0.004	0.007	0.14	3.97	1.07	0.01	4.29	0.01	0.05

TABLE II

INCLUSION COUNT ACCORDING TO JK CHARTS

(ASTM RECOMMENDED PRACTICE E 45-51)

Alloy	Melting process	Thin				Thick			
		A	B	C	D	A	B	C	D
52100	Electric furnace, heat 1	2.0	1.5	3.0	2.0	1.0	1.0	1.0	1.5
52100	Electric furnace, heat 2	2.0	1.5	2.0	3.0	0.5	1.0	1.0	1.0
52100	Electric furnace, heat 3	1.5	3.0	2.0	2.0	0	1.0	1.0	1.5
52100	Induction vacuum	0.5	[a]2.0	0.5	1.0	0	0	0	0
Halmo	Induction vacuum	0.5	2.0	0.5	2.0	0	0	0	0.5
MV-1	Induction vacuum	0.5	1.5	0.5	2.0	0	0.5	0	0.5
M-1	Induction vacuum	0	1.0	0	1.5	0	0	0	0

[a]One field; average rating, 1.0.

TABLE III

PROCESSING DATA

Alloy	Melting process	Type of heat treatment	Heat-treated by -	Approx. hardness, Rc	Heat treatment					
					Austenitizing temperature, °F	Quench	First temper		Second temper	
							Temp., °F	Time, hr	Temp., °F	Time, hr
52100 (Heat 1)	Electric furnace	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	1,535	Oil	320 320 320 320 300	0.5 .5 .5 .5 .33	775 600 525 350 -----	1 1 1 1 ---
52100 (Heat 2)	Electric furnace	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	1,535	Oil	320 320 320 320 300	0.5 .5 .5 .5 .33	785 700 545 365 -----	1 1 1 1 ---
52100 (Heat 3)	Electric furnace	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	1,535	Oil	320 320 320 320 300	0.5 .5 .5 .5 .33	785 700 545 365 -----	1 1 1 1 ---
52100	Induction vacuum	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	1,535	Oil	320 320 320 320 300	0.5 .5 .5 .5 .33	750 625 500 340 -----	1 1 1 1 ---
Halmo	Induction vacuum	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	[a]2,100	Air	1,000	2	1,145 1,115 1,090 1,060 -----	2 2 2 2 ---
Halmo	Induction vacuum	Commercial	Marlin-Rockwell Corp.	62	[a]2,100	Oil	1,000	2	1,000	2
Halmo	Induction vacuum	Commercial	Crucible Steel Co. of America	62	[b]2,100	Salt, 900° F	1,050	2	1,050	2
M-1	Induction vacuum	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	[a]2,200	Oil	1,000	2	1,200 1,170 1,150 1,120 -----	2 2 2 2 ---
M-1	Induction vacuum	Commercial	Marlin-Rockwell Corp.	62	[a]2,200	Oil	1,000	2	1,000	2
M-1	Induction vacuum	Commercial	Crucible Steel Co. of America	62	[b]2,200	Salt, 900° F	1,050	2	1,050	2
MV-1	Induction vacuum	Experimental	Marlin-Rockwell Corp.	50 54 58 62 65	[a]2,050	Oil	1,000	2	1,200 1,160 1,125 1,060 -----	2 2 2 2 ---
MV-1	Induction vacuum	Commercial	Marlin-Rockwell Corp.	62	[a]2,050	Oil	1,000	2	1,000	2
MV-1	Induction vacuum	Commercial	Crucible Steel Co. of America	62	[b]2,200	Salt, 900° F	1,050	2	1,050	2

[a]Preheat of 1,500° F.
[b]Preheat of 1,550° F

TABLE IV

EFFECTS OF ELEVATED TEMPERATURE ON MECHANICAL PROPERTIES OF VACUUM-MELTED BEARING STEELS AT A HARDNESS OF 62 Rc

Alloy	Test temp., °F	Tensile strength, psi	Tensile yield, psi	Compressive yield, psi	Fatigue strength at 10^7 cycles, psi
52100	Room	340,000	240,000	400,000	130,000
	350	340,000	260,000	290,000	95,000
Halmo	Room	370,000	310,000	410,000	140,000
	500	335,000	310,000	340,000	110,000
M-1	Room	370,000	310,000	420,000	130,000
	500	350,000	300,000	355,000	110,000
MV-1	Room	370,000	295,000	340,000	125,000
	500	335,000	300,000	340,000	100,000

TABLE V

TABULATED DATA OBTAINED FROM X-RAY MEASUREMENTS

Alloy and melting process	Data at hardnesses, Rc, of -					
	Code (a)	50	54	58	62	65
52100, electric furnace	d	1.1704	1.1708	1.1713	1.1726	1.1731
	I_p	320	250	225	130	125
	w-1/2 . . .	1.7	2.1	2.55	3.0	3.4
	c	------	------	------	------	Trace
	A	------	------	------	Trace	Trace
52100, induction vacuum	d	1.1697	1.1702	------	1.1708	1.1713
	I_p	320	285	------	180	140
	w-1/2 . . .	1.7	2.1	------	3.1	3.5
	c	------	------	------	------	-------
	A	------	------	------	Trace	Trace
Halmo, induction vacuum	d	------	1.1706	1.1717	1.1719	1.1721
	I_p	------	270	205	200	170
	w-1/2 . . .	------	2.05	2.6	2.45	3.0
	c	------	------	Trace	Weak	Weak
	A	------	------	Trace	Weak	Weak
M-1, induction vacuum	d	1.1710	1.1713	1.1715	1.1728	1.1749
	I_p	220	195	195	170	90
	w-1/2 . . .	1.7	1.95	2.05	2.35	2.85
	c	Strong	Strong	Strong	Strong	Strong
	A	------	Trace	Trace	Trace	Strong
MV-1, induction vacuum	d	1.1708	1.1710	1.1721	1.1731	[b]1.1735
	I_p	285	260	225	170	155
	w-1/2 . . .	1.7	1.95	2.2	2.7	2.8
	c	------	------	------	------	-------
	A	------	Weak	Weak	Weak	Weak

[a]Code:

d	interplanar spacing, A
I_p	peak intensity of (211) diffraction line, counts per second
w-1/2	diffraction line width of (211) reflection at half intensity, $^{o}\theta$
c	carbide indication
A	austenite indication

[b]Hardness of 64 Rc for this specimen.

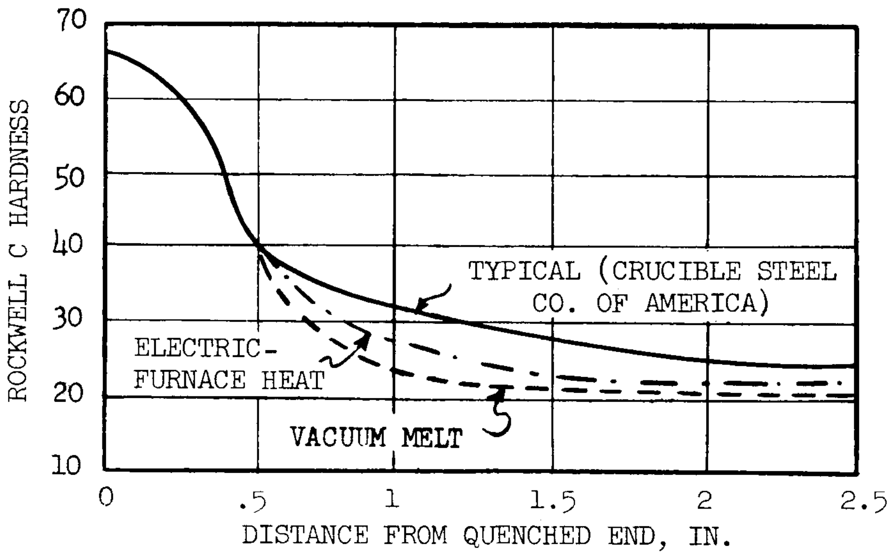
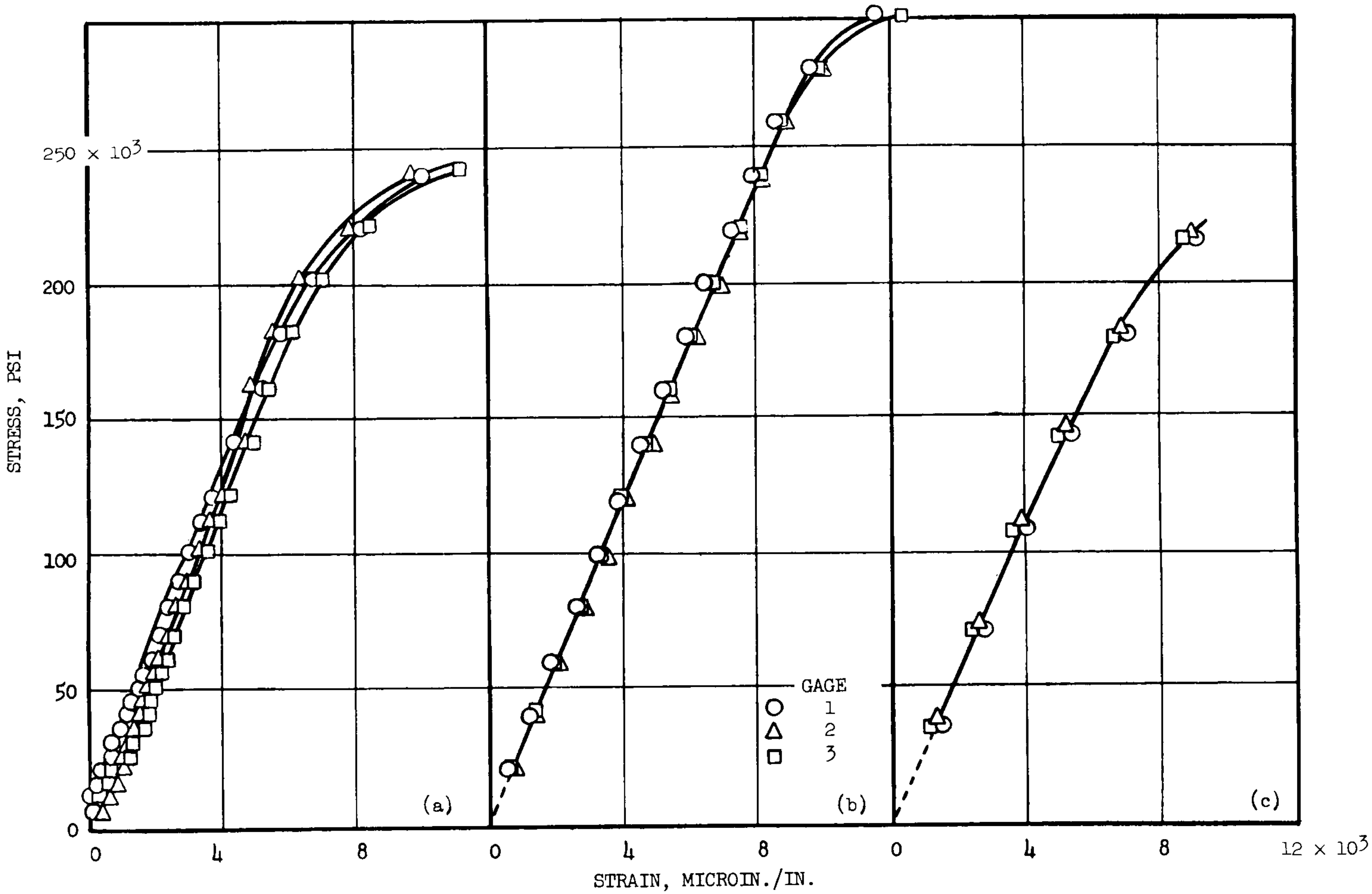


Figure 1.- Hardenability of 52100 steels.

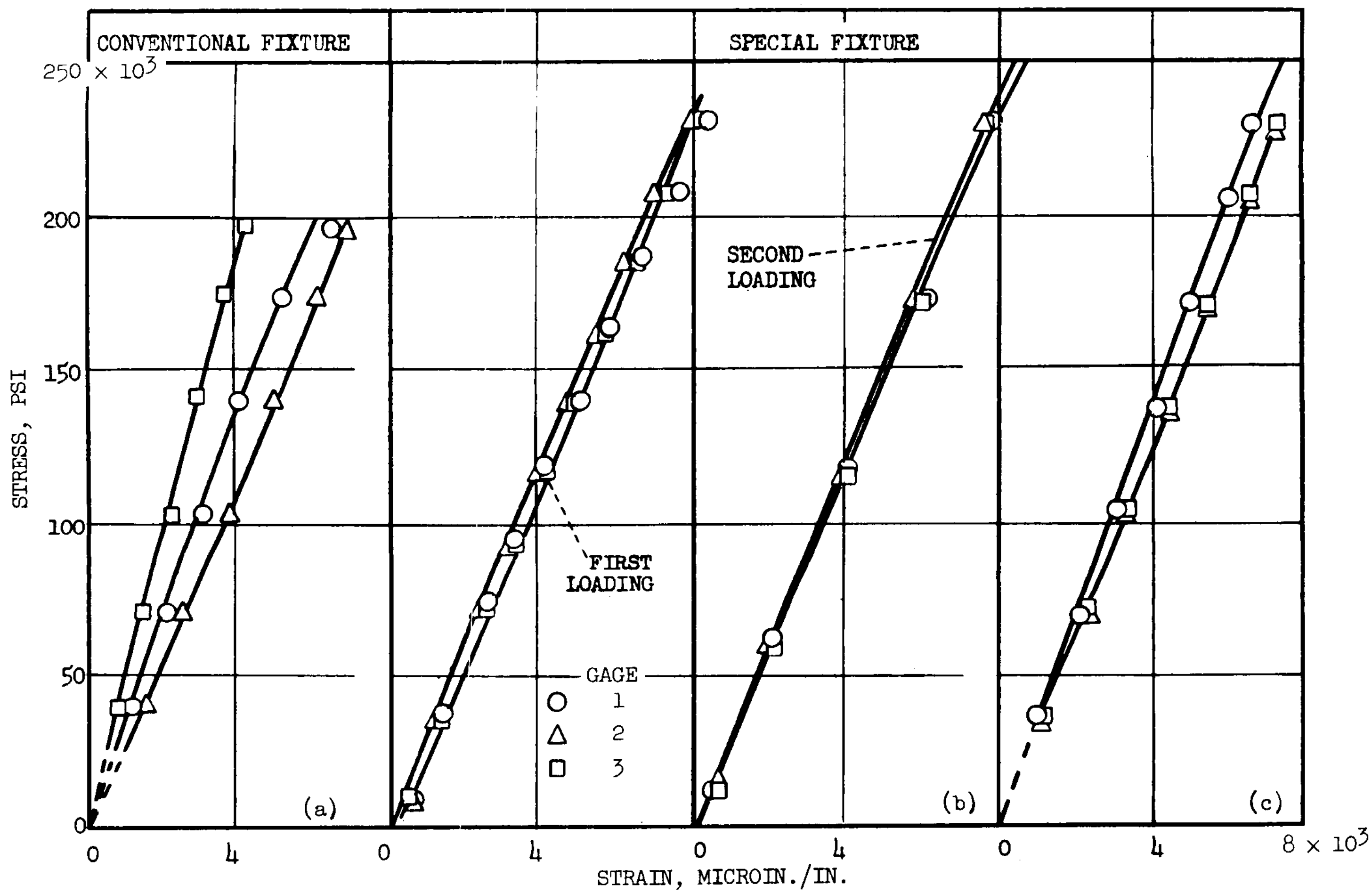


(a) Conventional fixture; heat 1; specimen 1; 50 Rc.

(b) Notch tension fixture; specimen 34; 58 Rc.

(c) Notch tension fixture; specimen 57; 65 Rc.

Figure 2.- Strain-gage data for concentricity tests in tension on 52100 steel.



(a) Conventional fixture; 4340 steel; specimen 2.

(b) Special fixture; heat 1 of 52100 steel; specimen 47; 65 Rc.

(c) Special fixture; heat 1 of 52100 steel; specimen 36; 58 Rc.

Figure 3.- Strain-gage data for concentricity tests in compression.

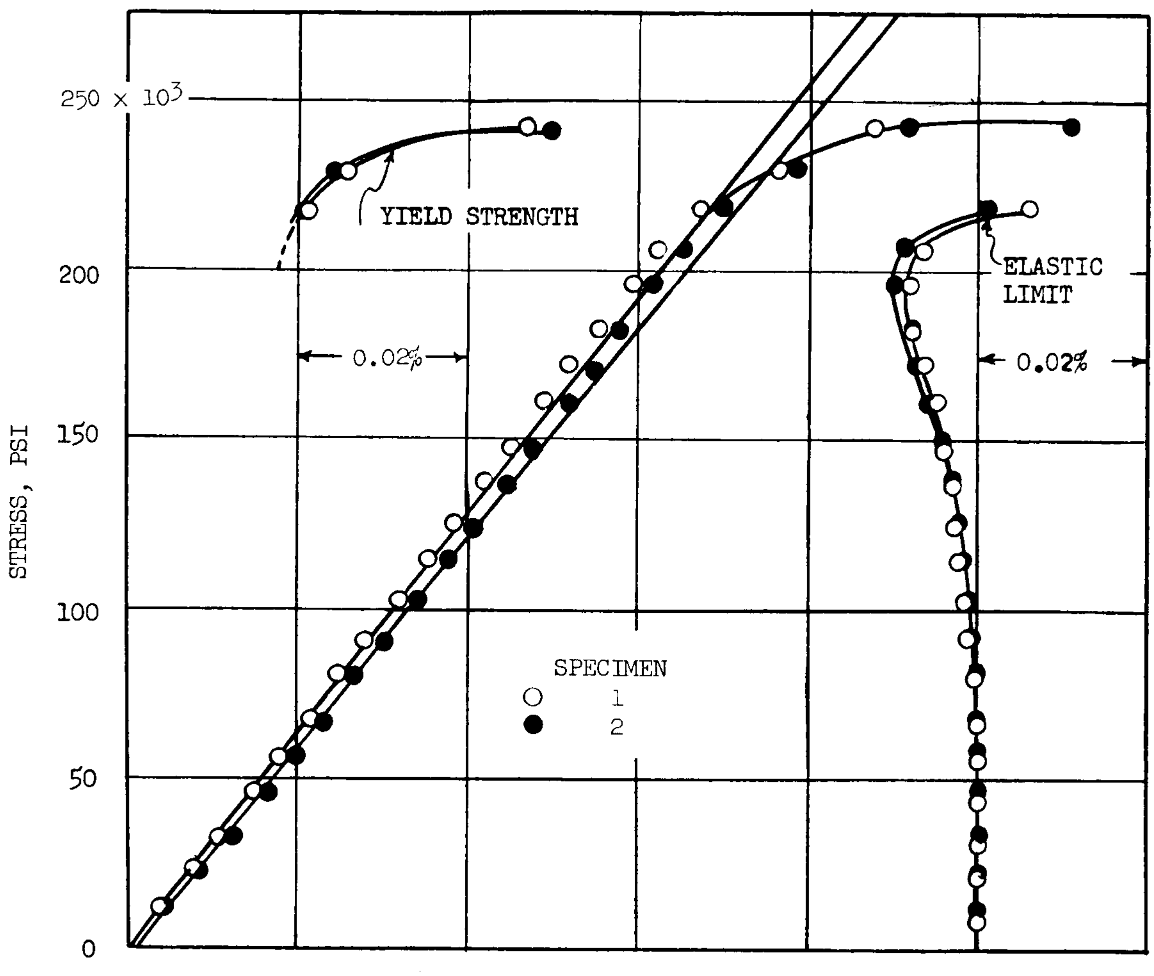


Figure 4.- Strain-gage readings for two specimens of heat 3 electric-furnace-melted 52100 steel showing strains under load and permanent strain after load release. Hardness, 58 Rc.

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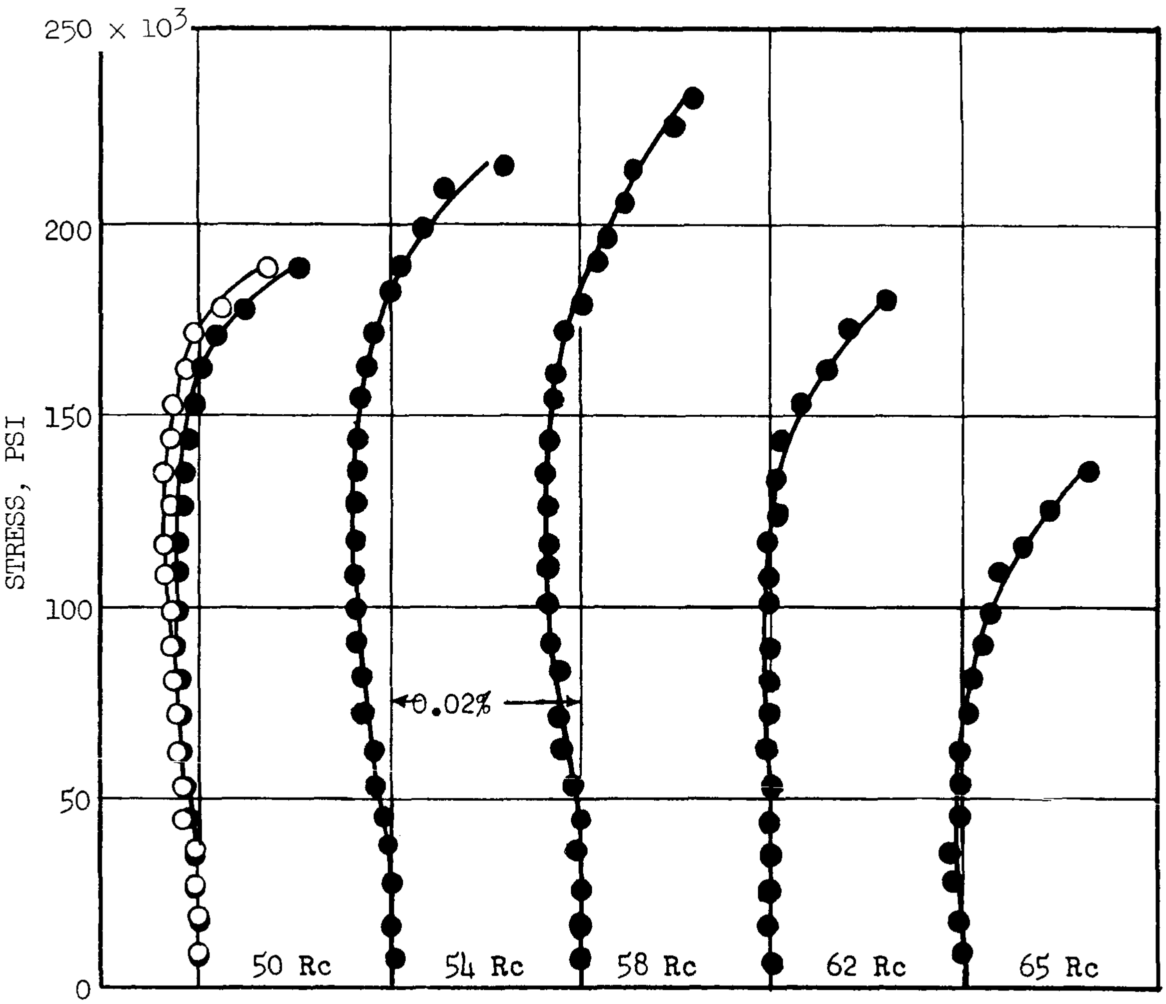
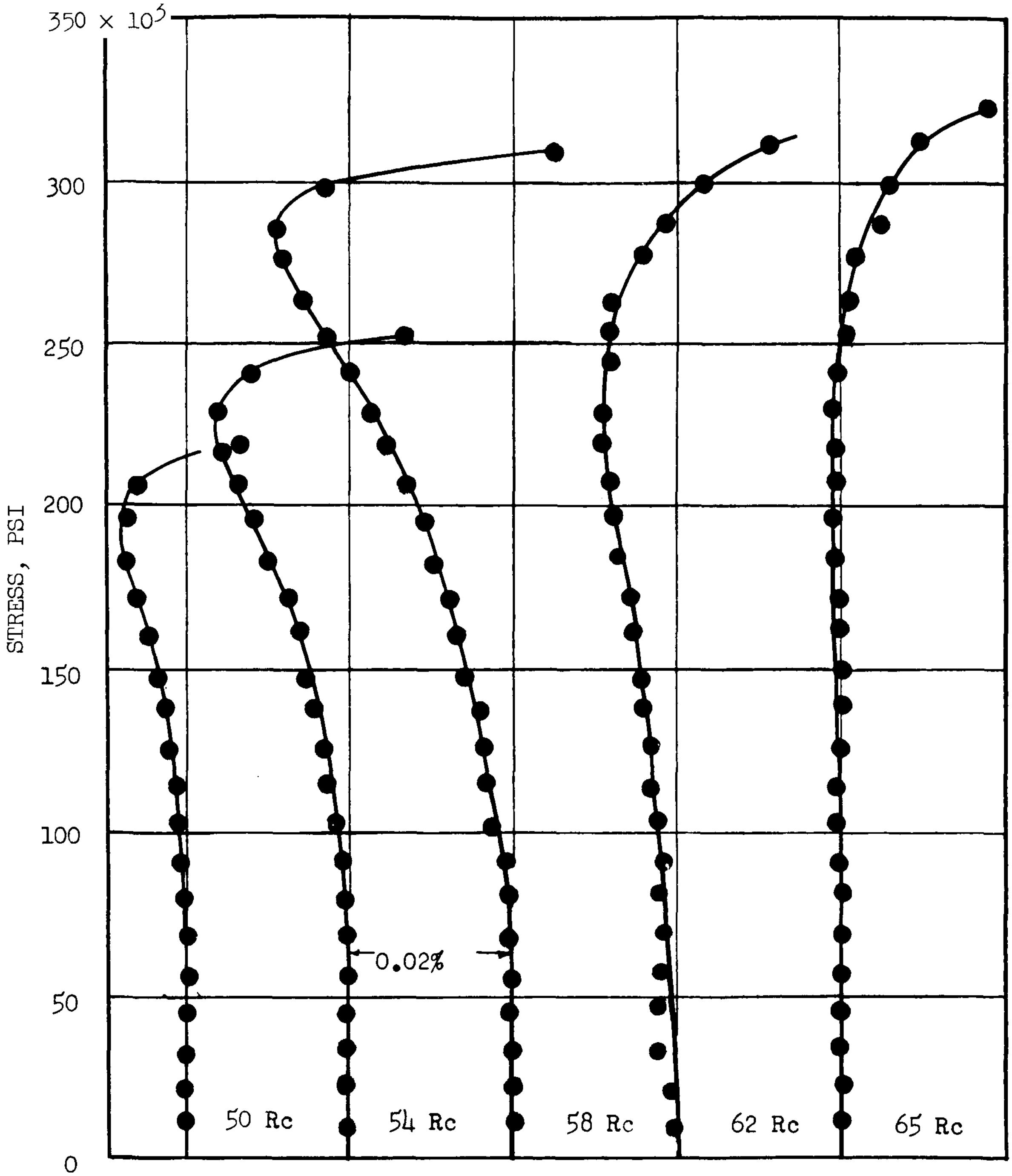


(a) Tension tests.

Figure 5.- Examples of strain-gage readings after load release for heat 3 of electric-furnace-melted 52100 steel.



(b) Compression tests.

Figure 5.- Concluded.

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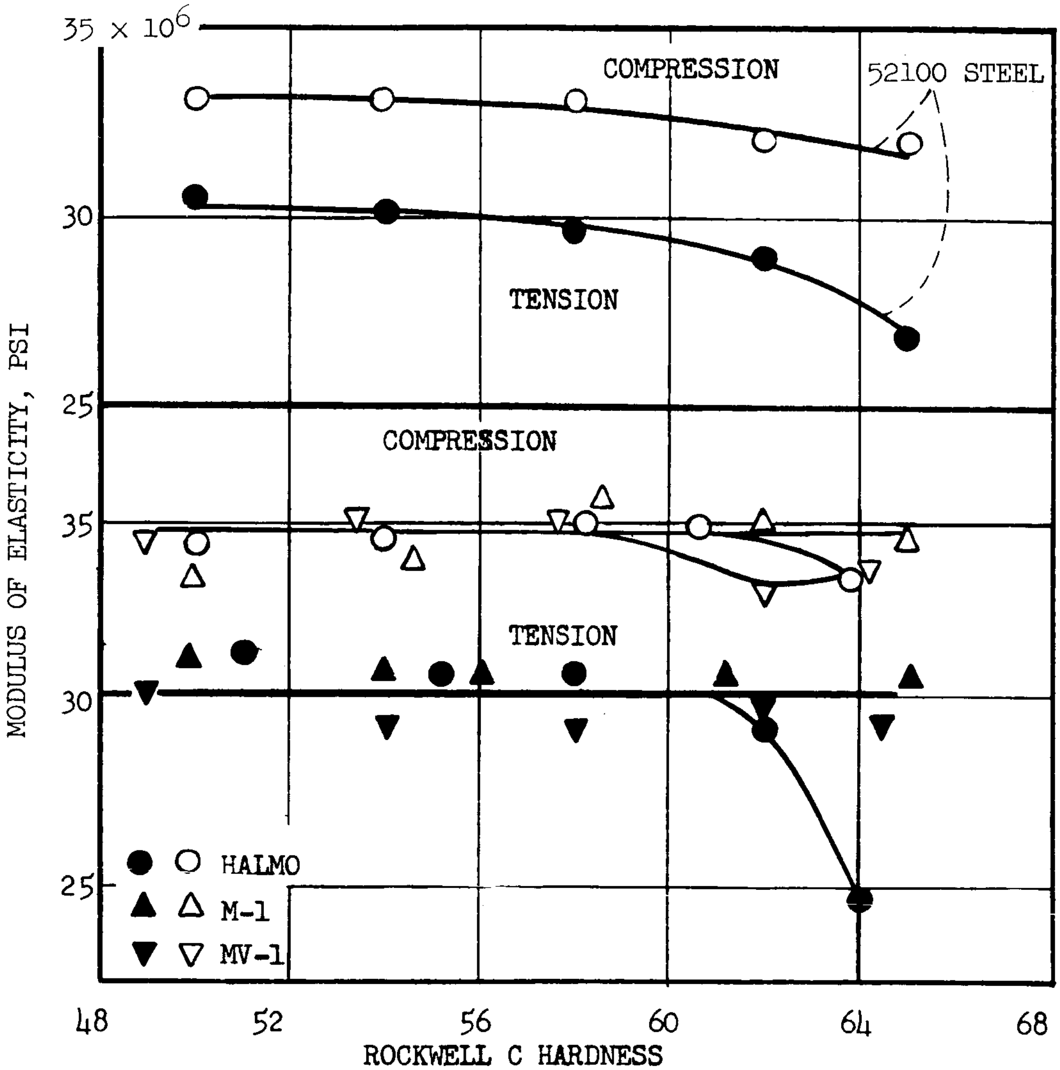
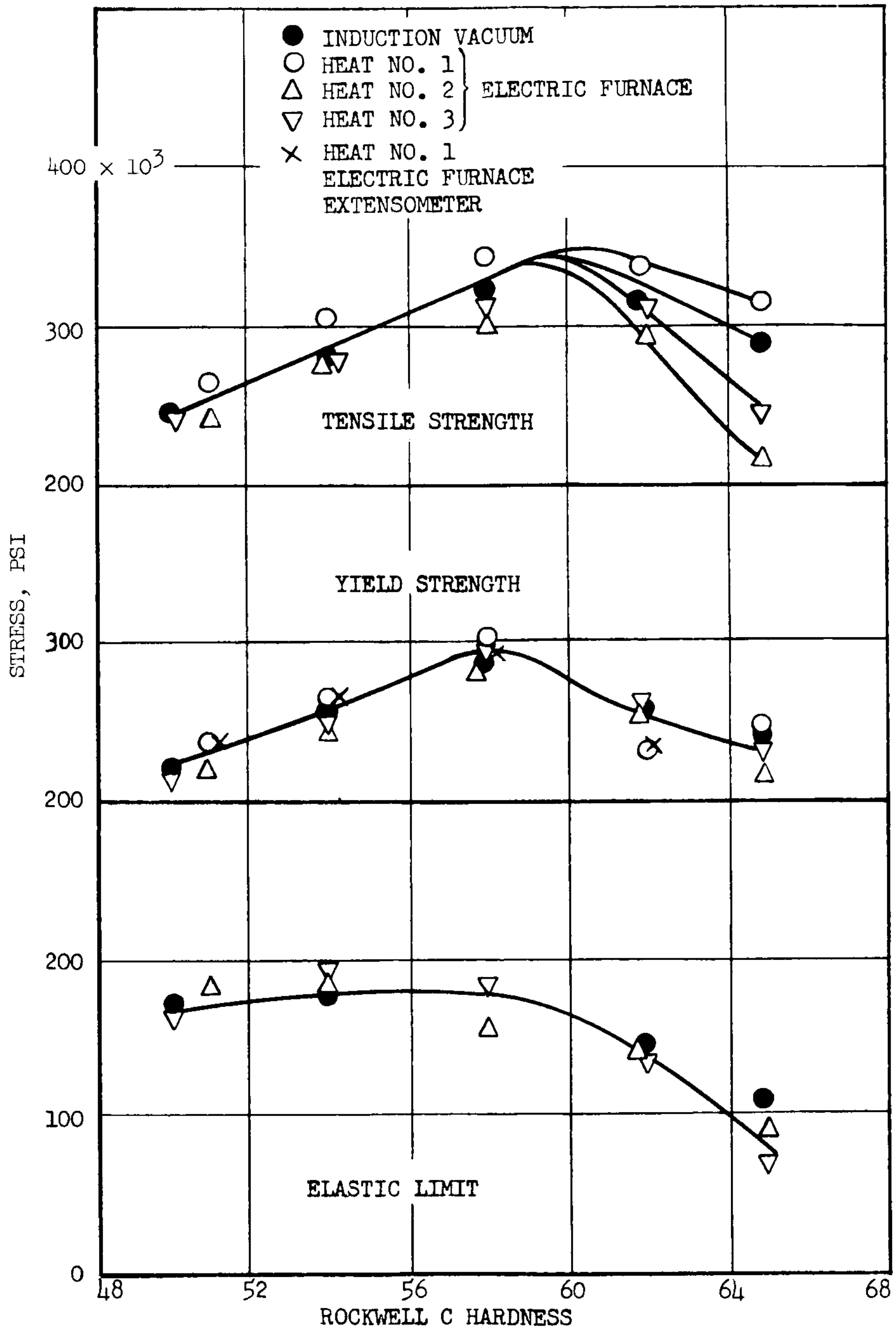
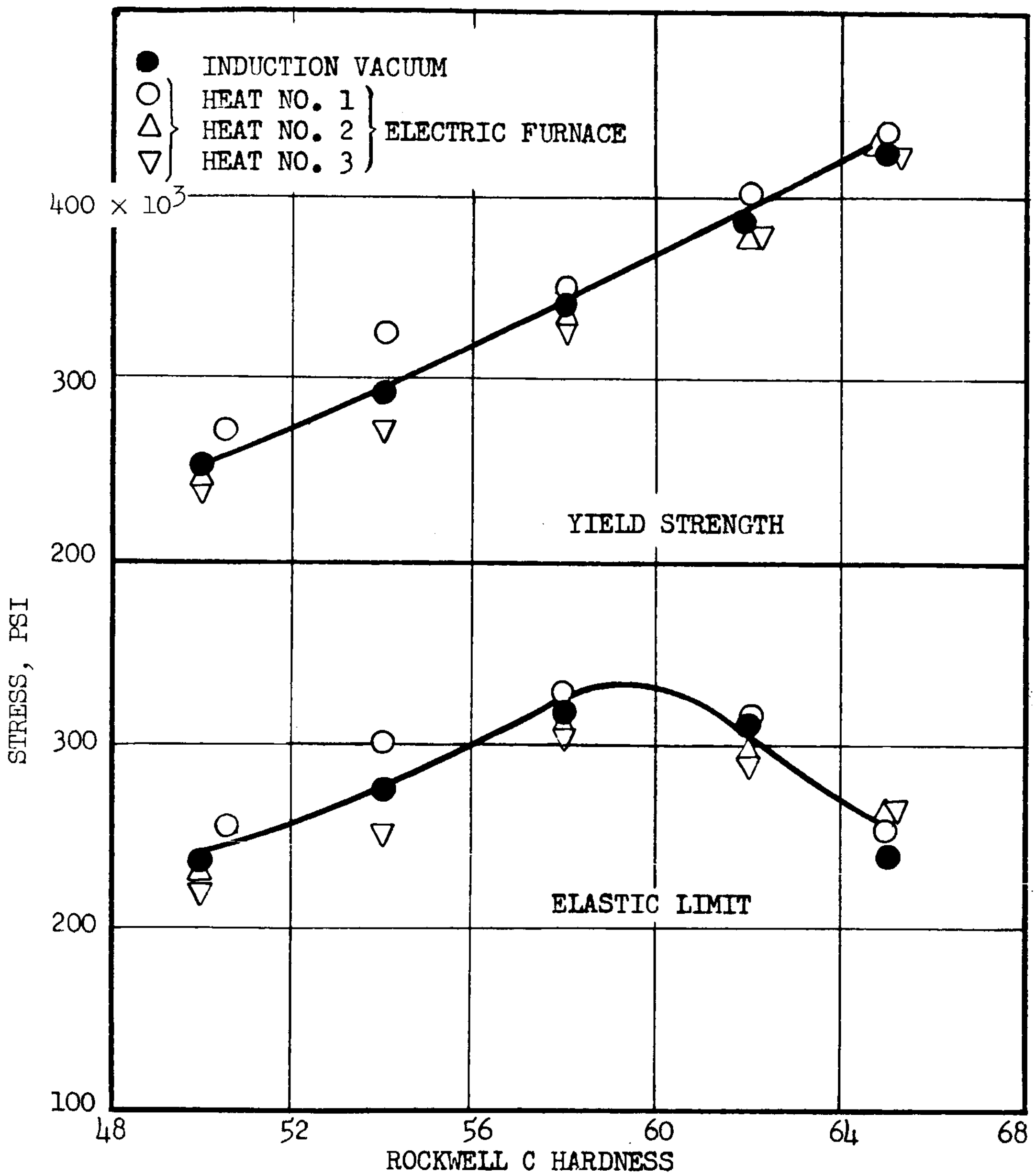


Figure 6.- Relation between modulus of elasticity and hardness of bearing steels.



(a) Tension properties.

Figure 7.- Tension and compression properties of 52100 steel tested at room temperature.



(b) Compression properties.

Figure 7.- Concluded.

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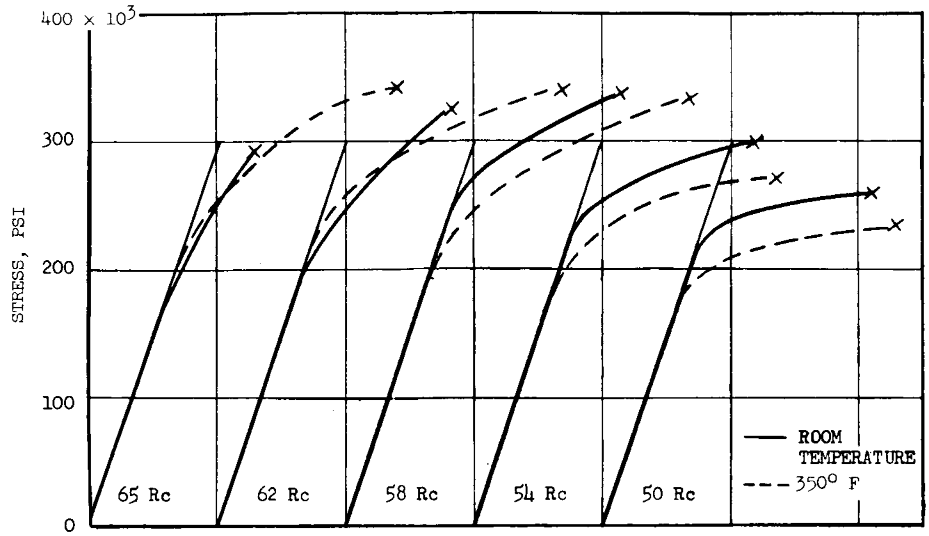
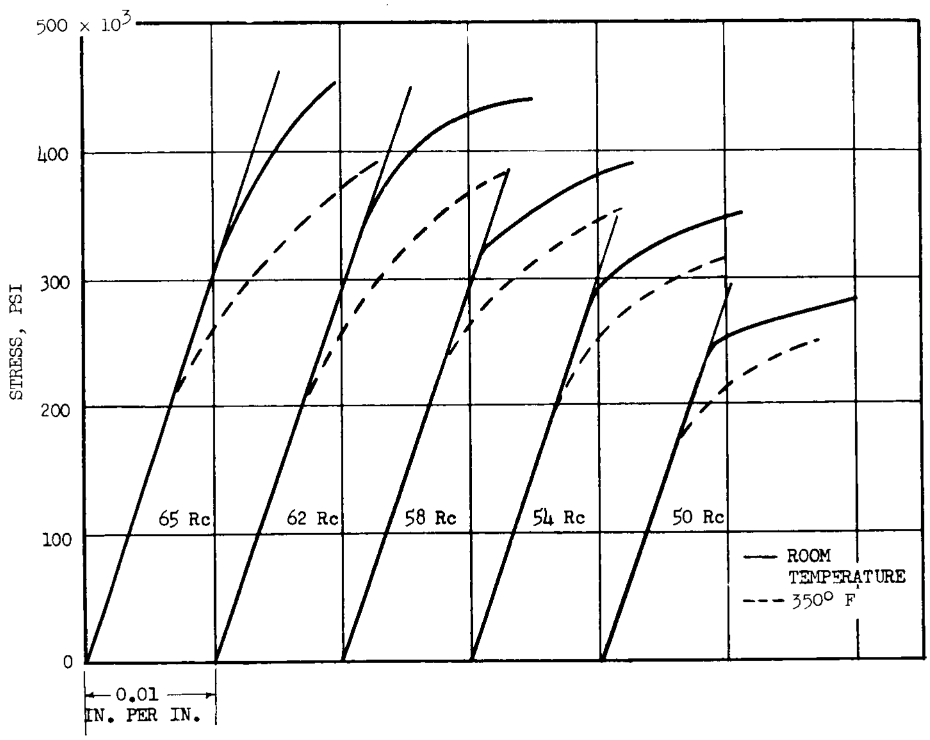


(a) Tension.



(b) Compression.

Figure 8.- Typical stress strain curves of 52100 steel in tension and compression.

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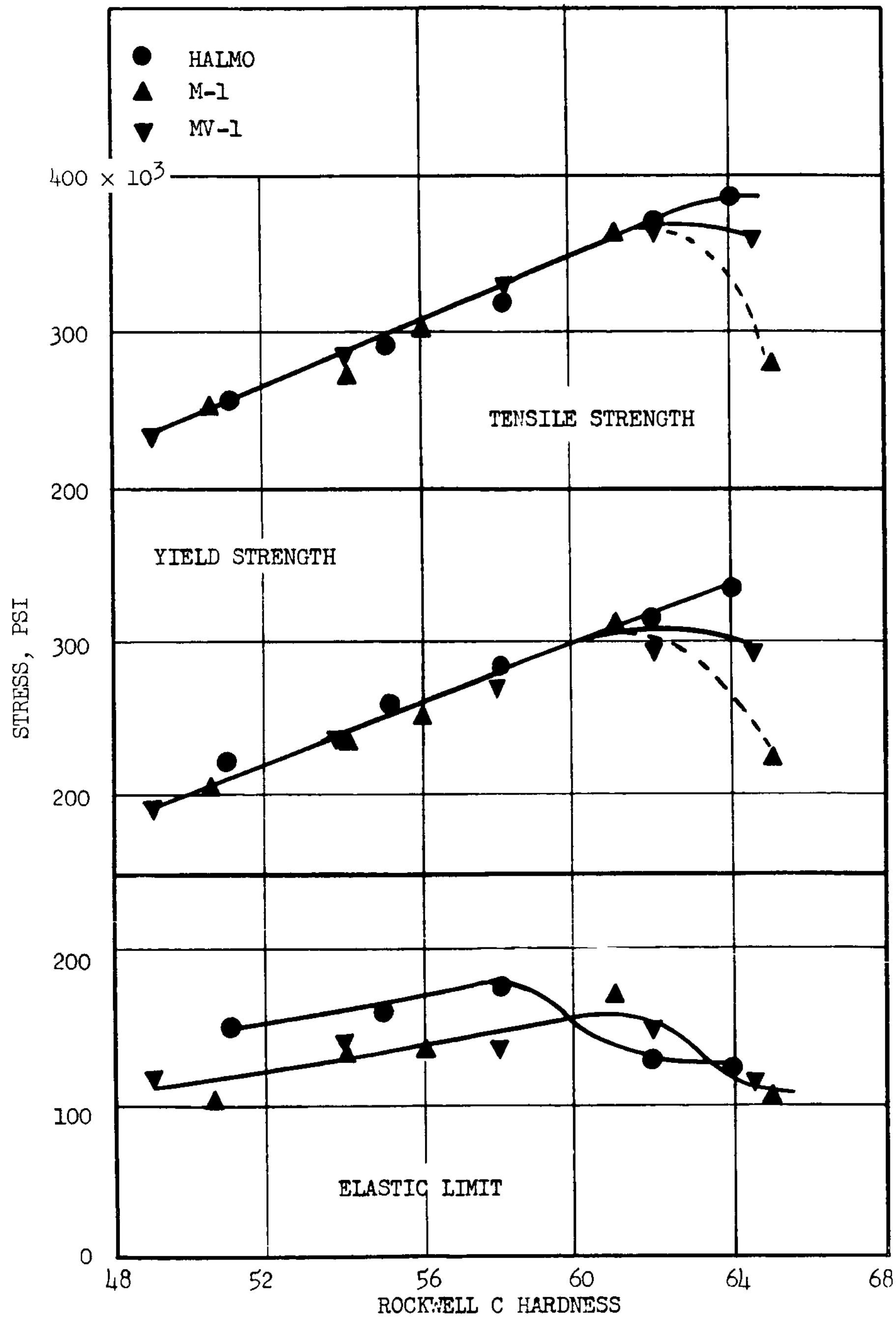
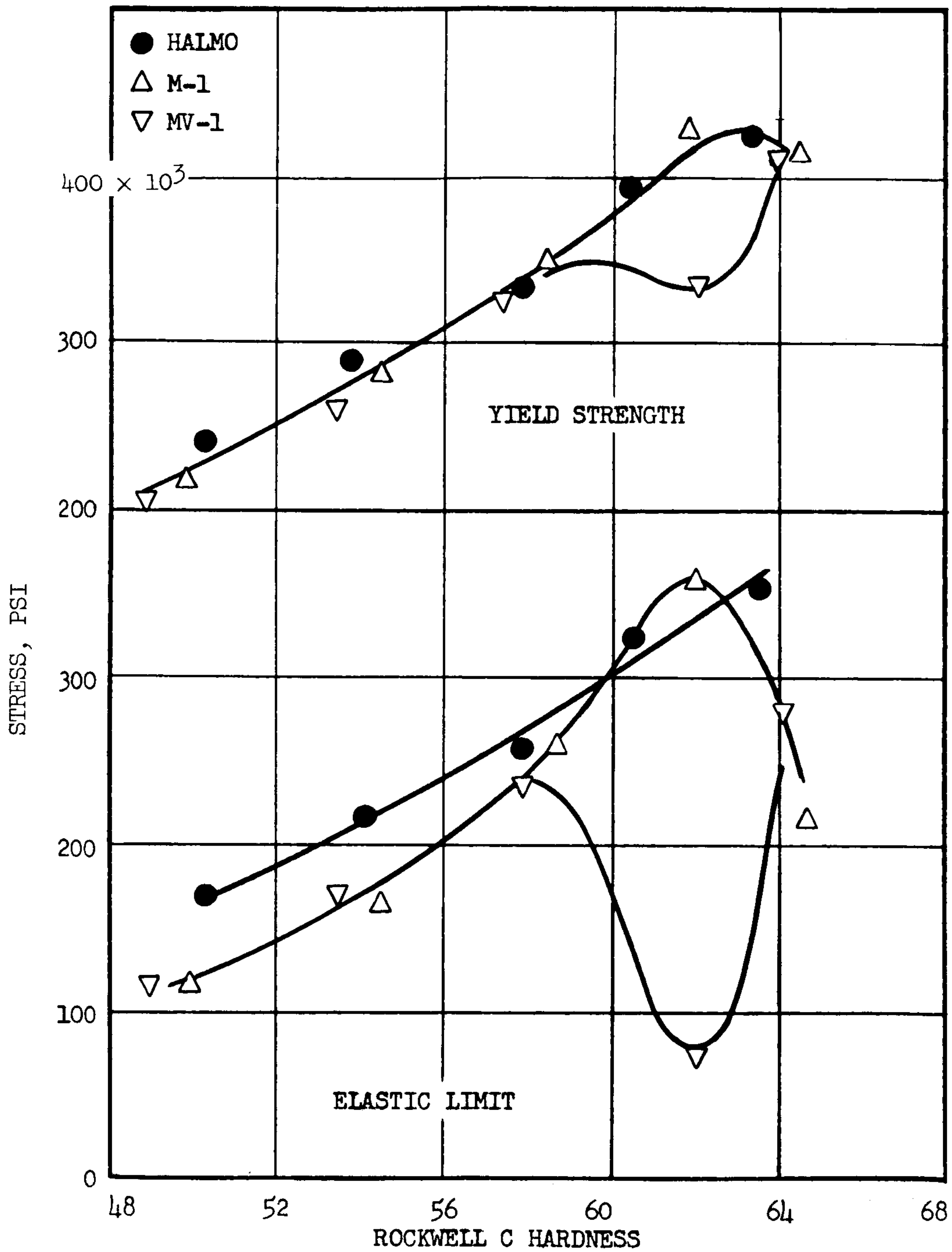


(a) Tension properties.

Figure 9.- Tension and compression properties of tool steels tested at room temperature.



(b) Compression properties.

Figure 9.- Concluded.

W-131

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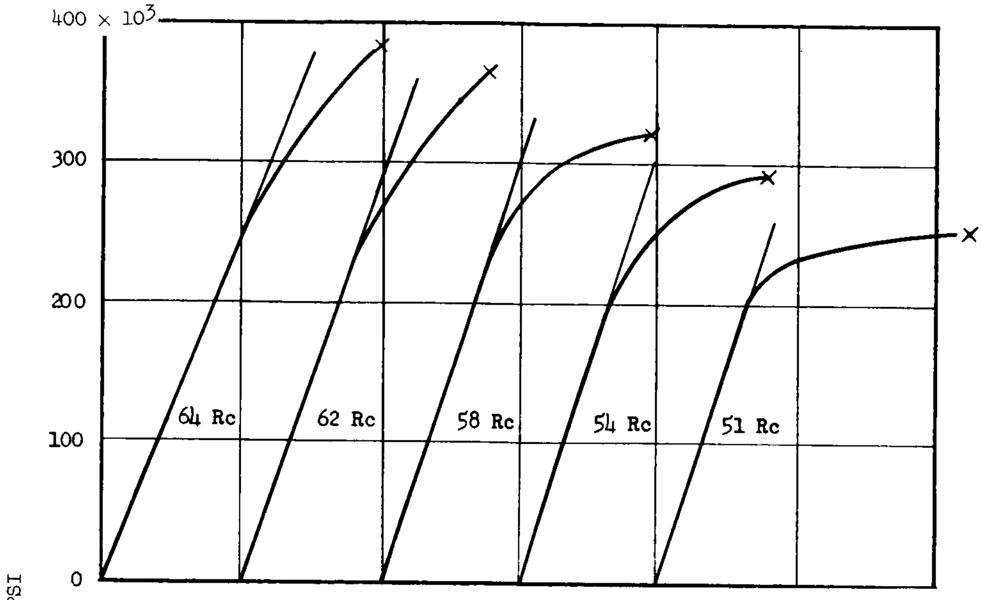
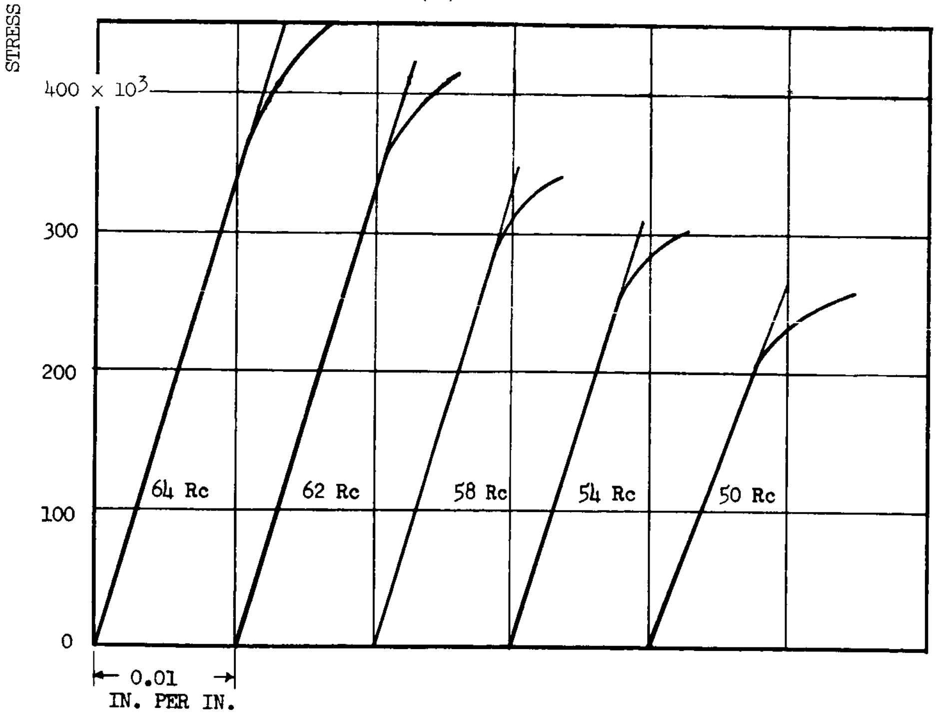


(a) Tension.



(b) Compression.

Figure 10.- Typical stress strain curves of Halmo steel in tension and compression.

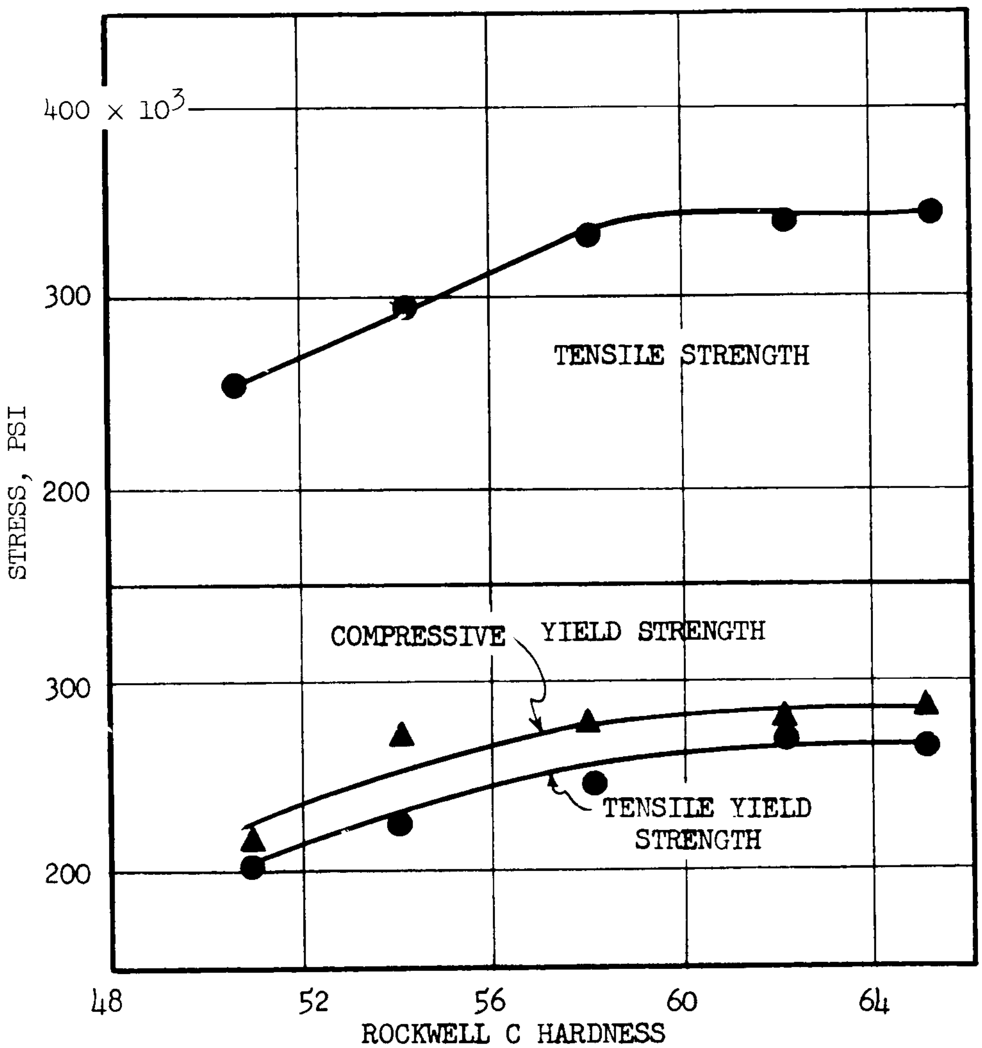


Figure 11.- Properties of 52100 steel at 350° F.

W-131

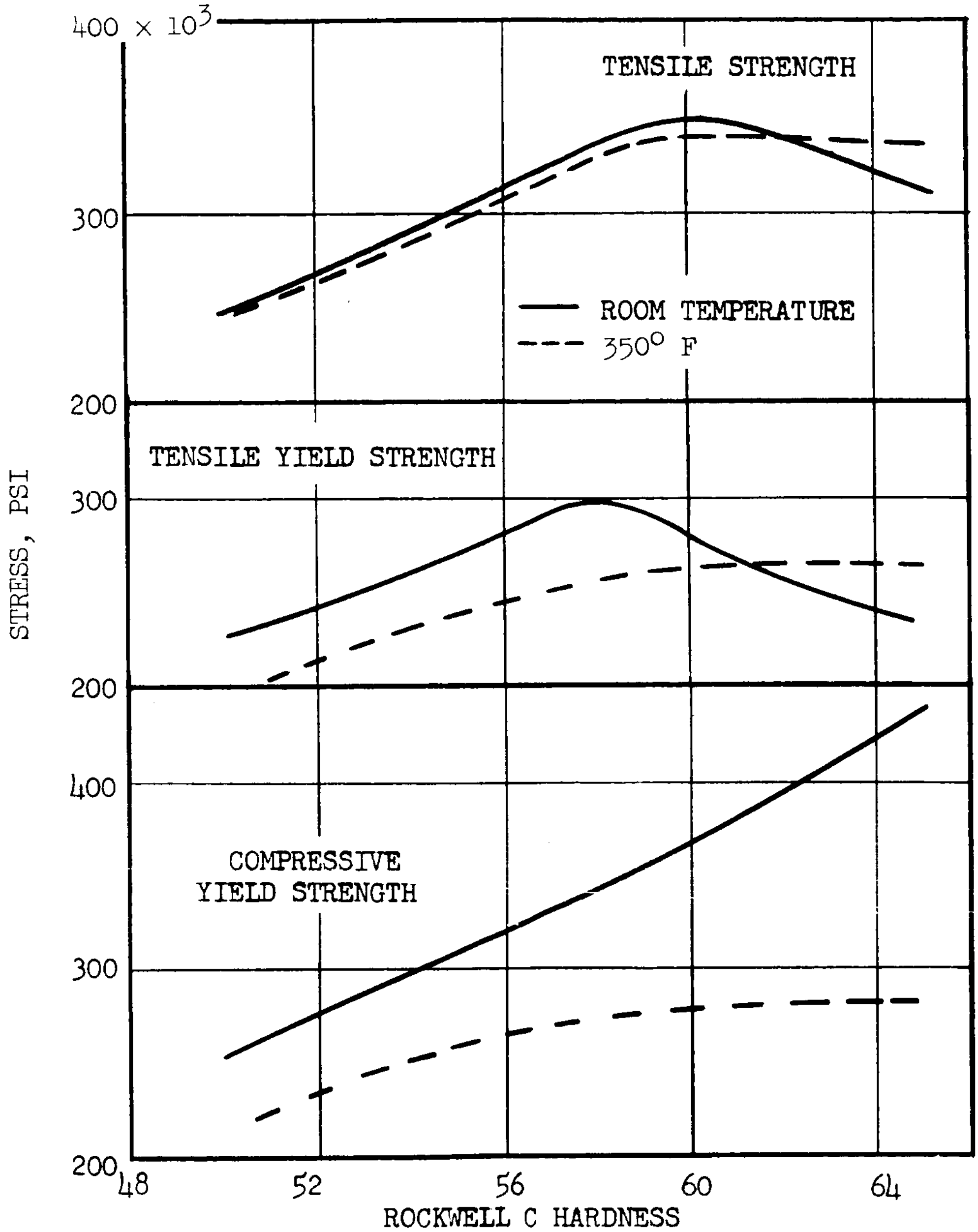
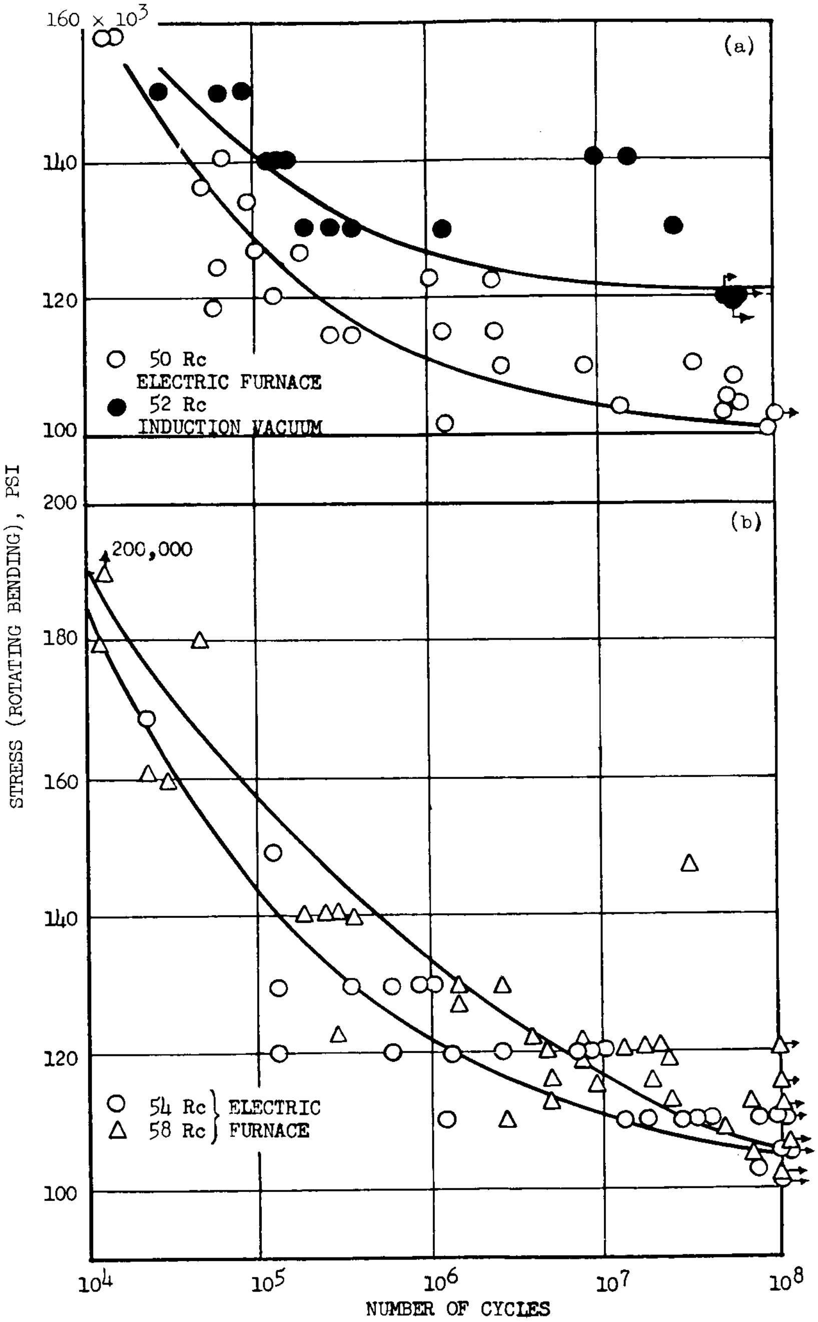


Figure 12.- Comparison of properties of 52100 steel at room temperature and 350° F.

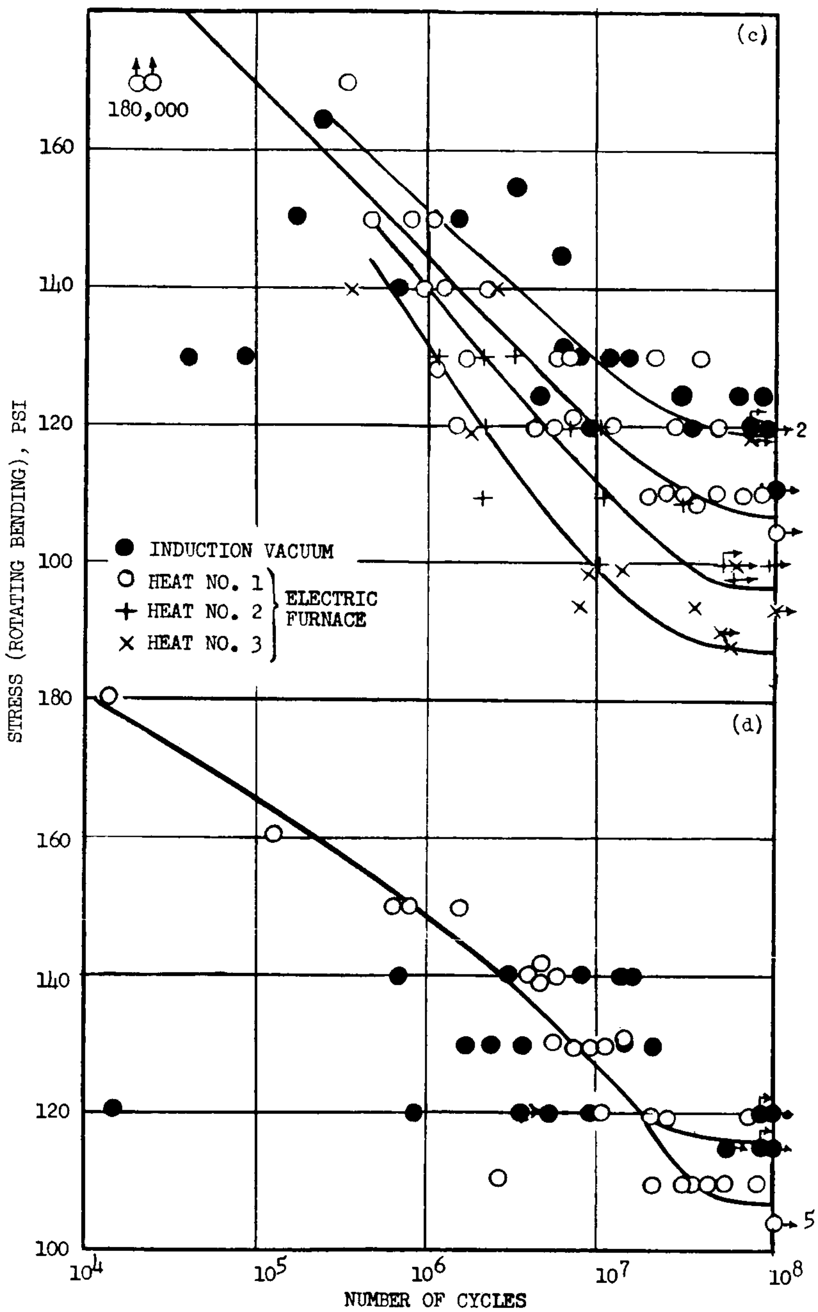


(a) Hardnesses of 50 and 52 Rc.

(b) Hardnesses of 54 and 58 Rc.

Figure 13.- S-N curves of 52100 steels at room temperature.

W-131



(c) Hardness of 62 Rc.

(d) Hardness of 65 Rc.

Figure 13.- Concluded.

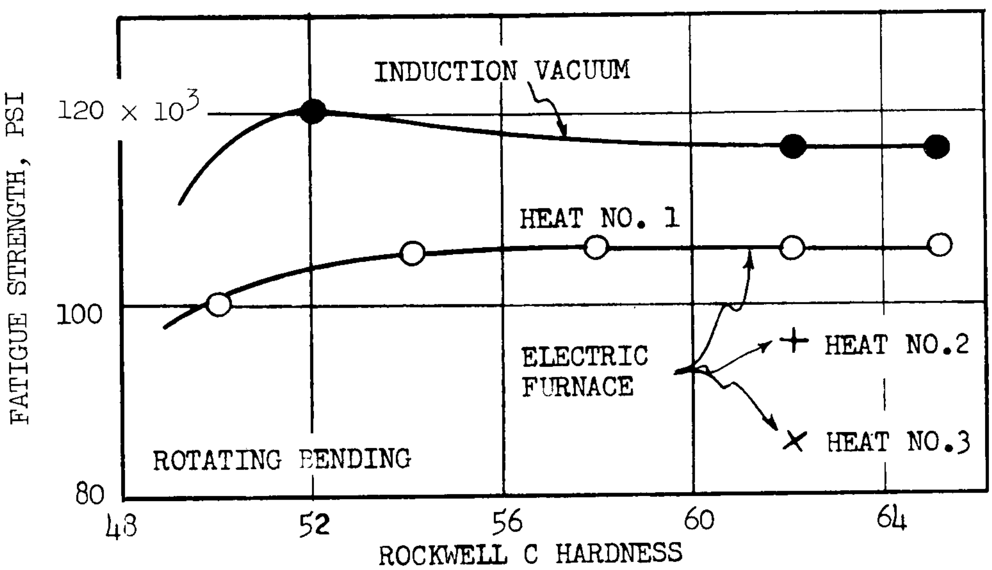


Figure 14.- Relation between endurance limit at 10^8 cycles in rotating-bending fatigue tests of 52100 steels and hardness at room temperature.

W-131

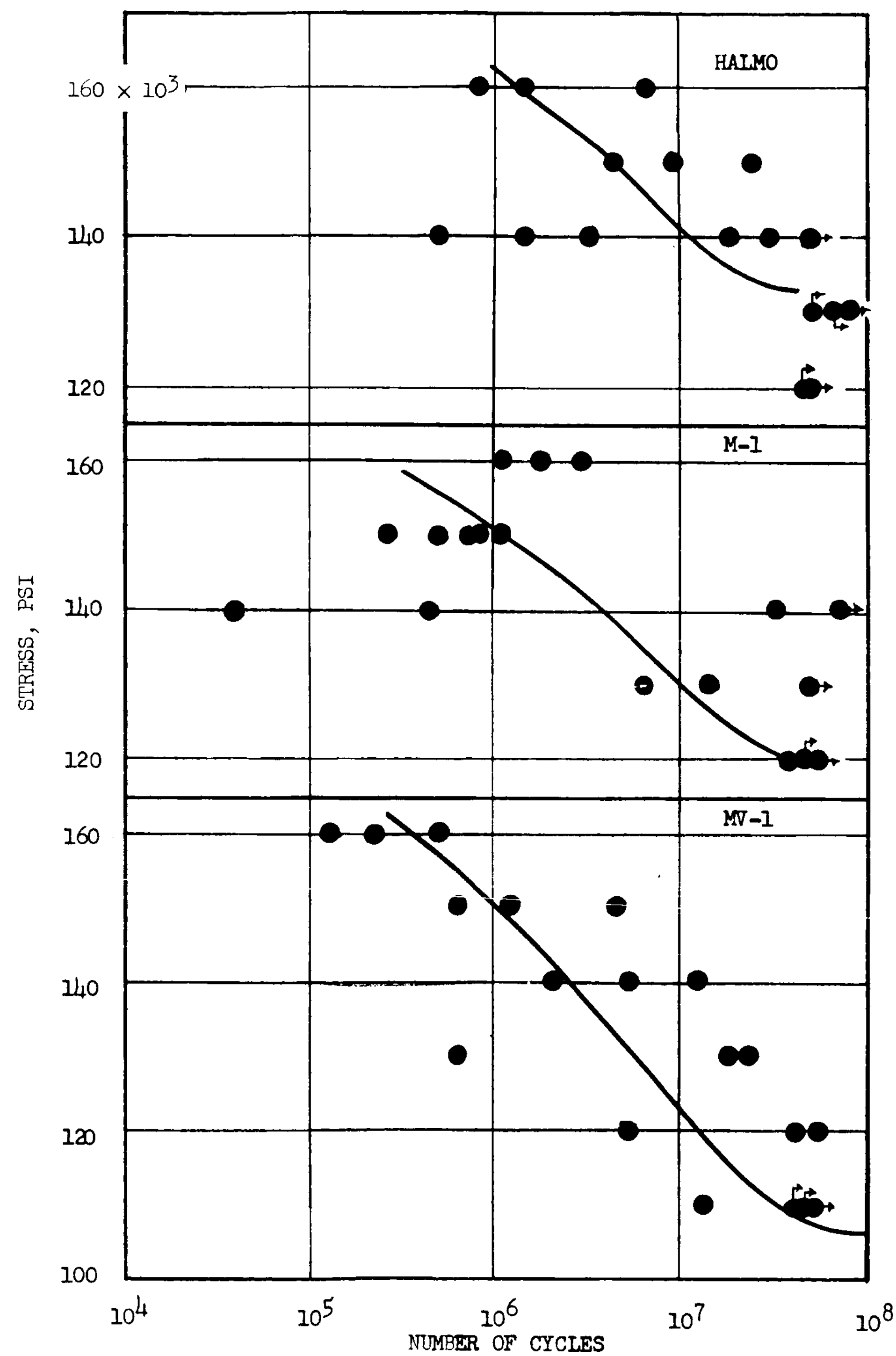


Figure 15.- S-N curves of tool steels of 62 Rc hardness at room temperature for rotating-bending fatigue tests.

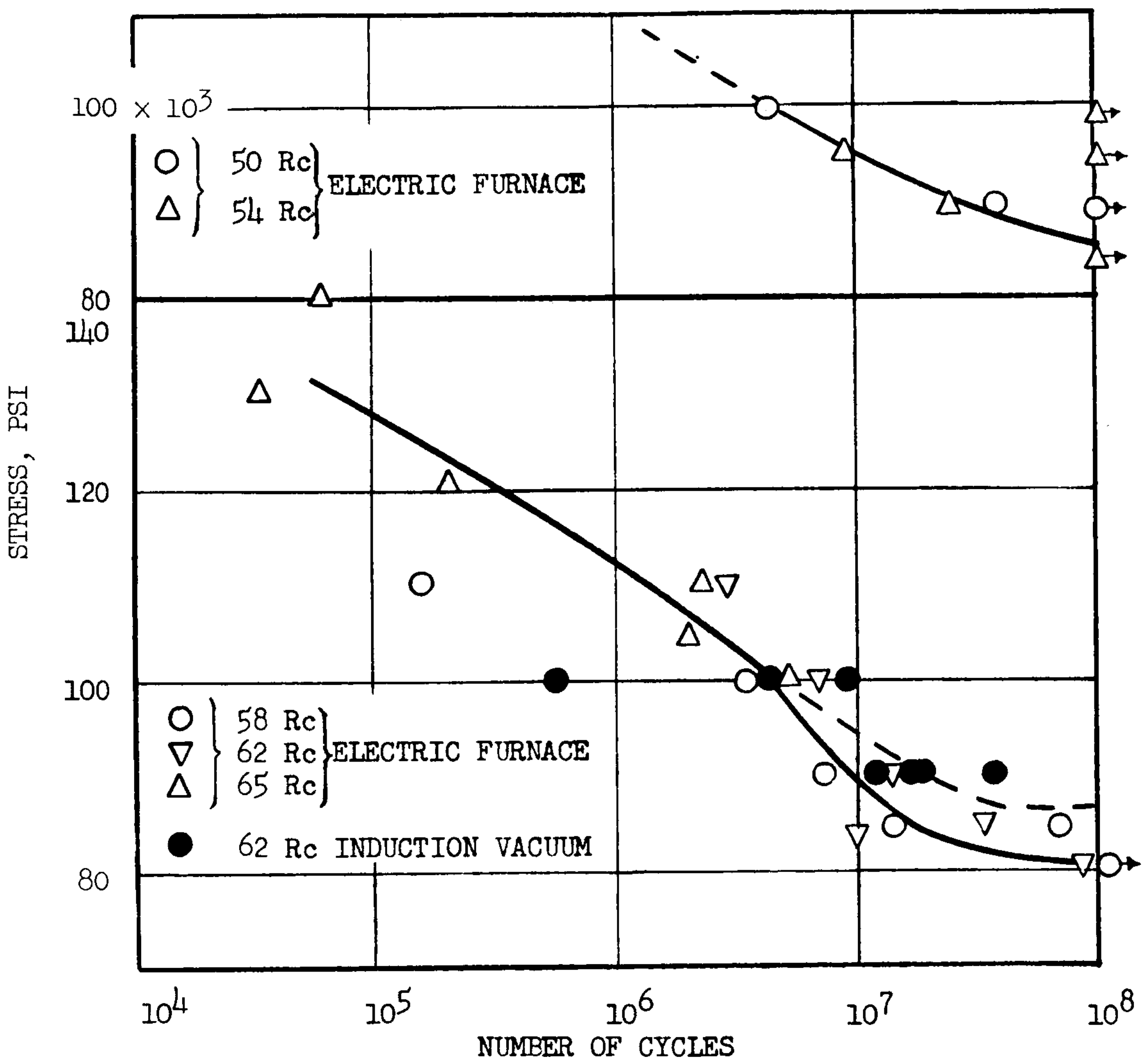


Figure 16.- S-N curves of 52100 steels at 350° F for rotating-bending fatigue tests.

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W-131

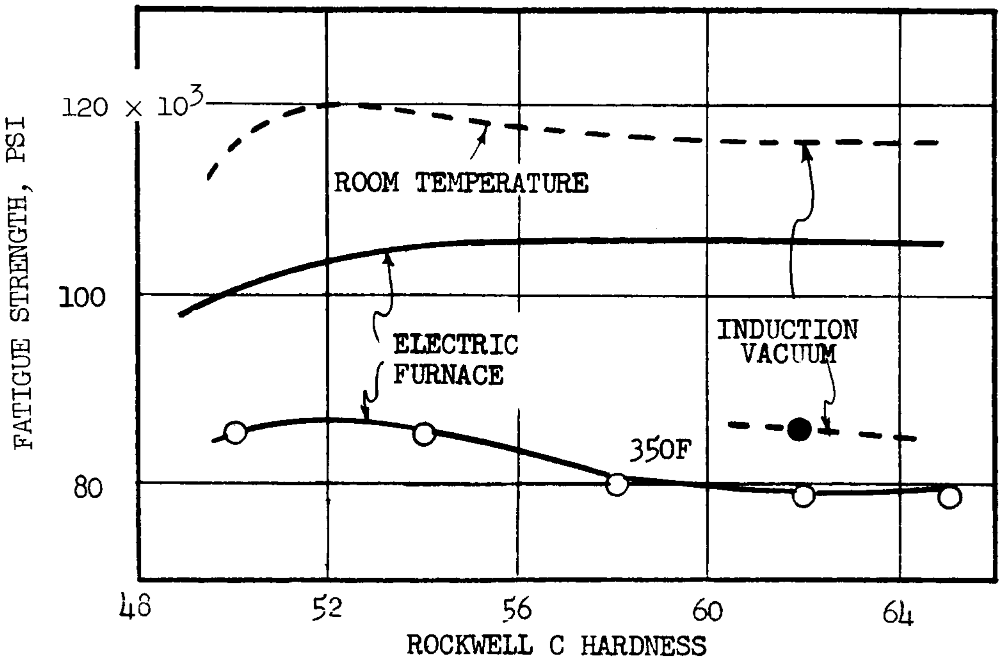

Figure 17.- Relation between endurance limit at 10^8 cycles in rotating-bending fatigue tests of 52100 steels and hardness at 350° F.

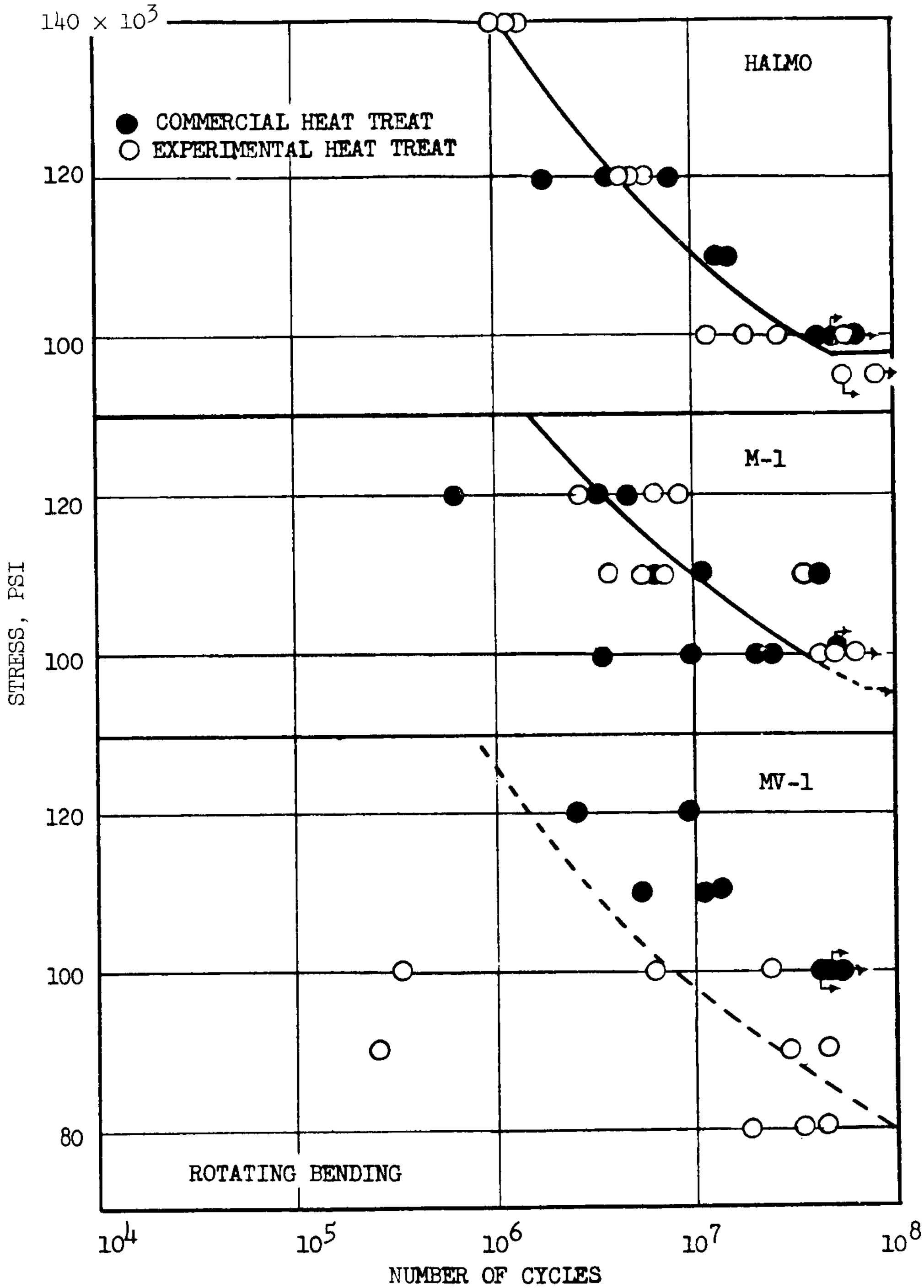

Figure 18.- S-N curves for tool steels of 62 Rc hardness at 500° F for rotating-bending fatigue tests.

W-131

W-131

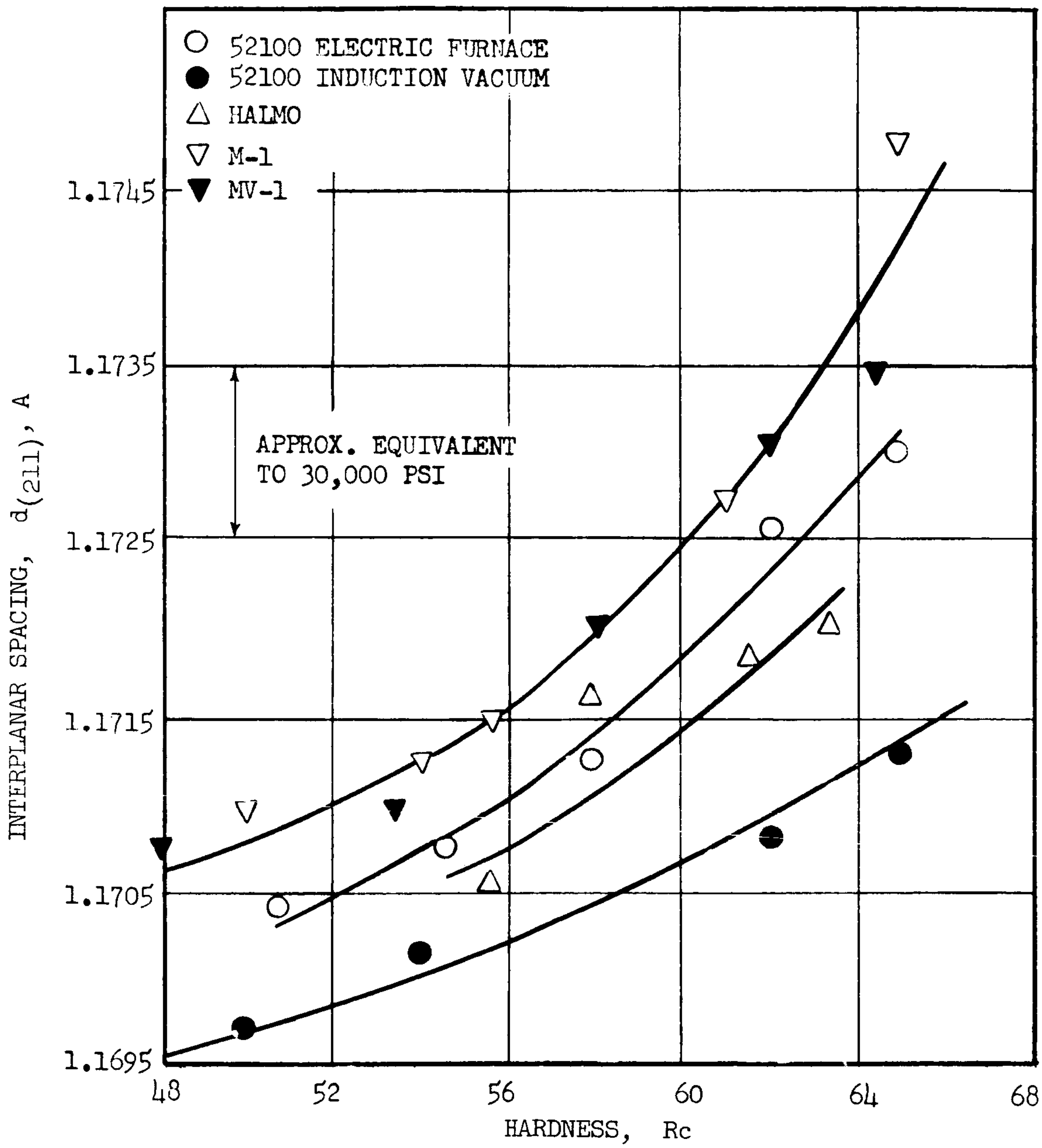

Figure 19.- Interplanar spacing of (211) planes as a function of hardness for indicated tool steels.

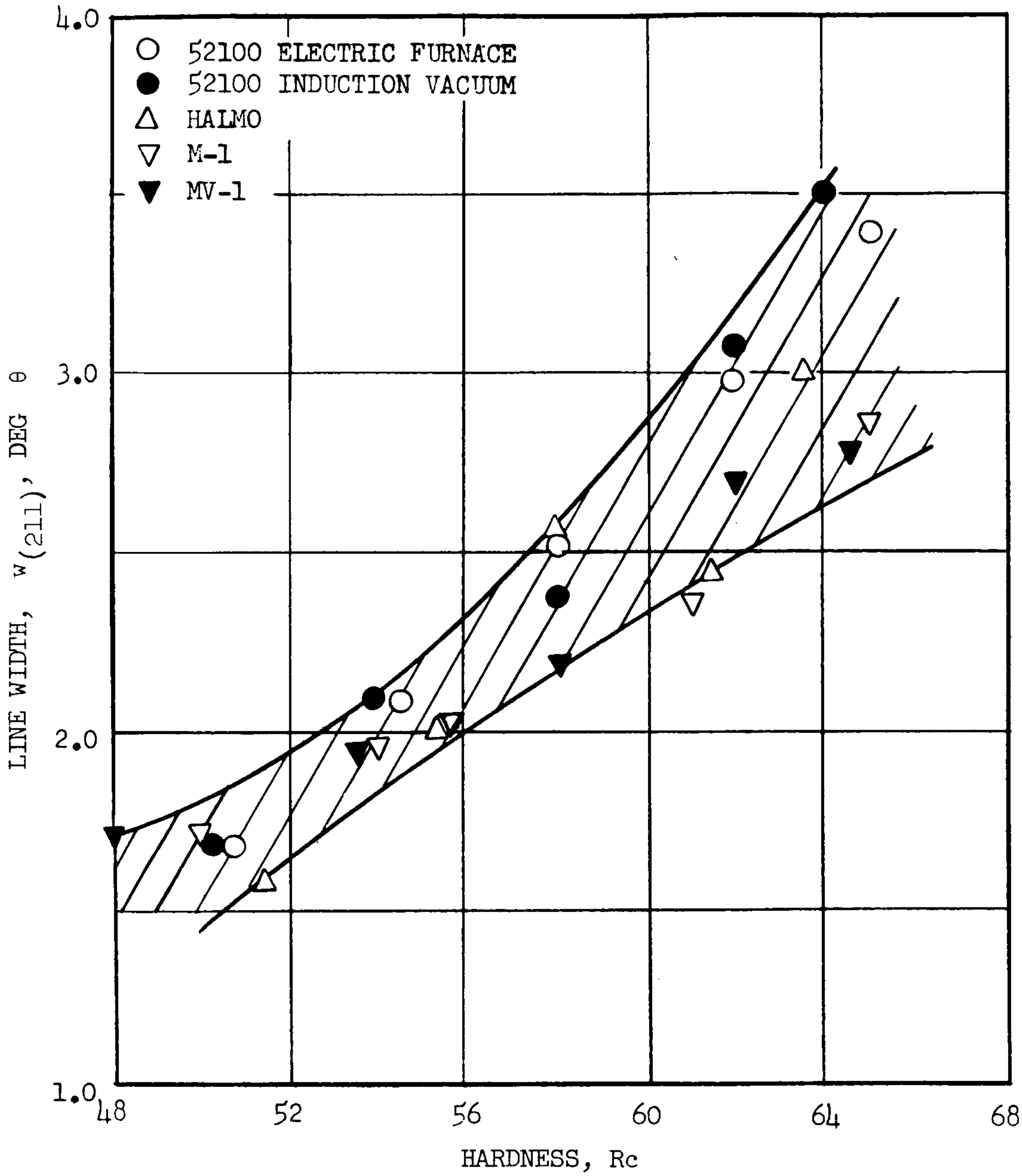

Figure 20.- Mean width of CrK_2 (211) diffraction line as function of hardness for indicated tool steels. 1° corresponds to a microstrain of approximately 2×10^{-3}.

W-131